SHAKE TABLE TESTS FOR ISOLATED BRIDGE MODEL USING STRUCTUAL CONTROL DEVICES

Takao Okada[1] and Shigeki Unjoh[2]

Abstract

This study aims to evaluate the seismic response of isolated bridge model using sliding bearings and dampers. Shake table tests of bridge model and the numerical analyses were performed. The result of shake table tests showed that the superstructure inertia force was decreased by sliding bearing and dampers. The simple analytical model could approximately simulate the test results.

Introduction

The seismic isolation bridges using high damping bearings such as lead rubber bearings and high damping rubber bearings have been constructed since 1995 Hyogo-ken Nanbu Earthquake. These rubber bearings generally become larger because they have functions to support vertical and horizontal forces and to absorb rotational deformation. The large clearance between deck end and abutment and large expansion joints are generally needed. In recent years, therefore, new type bearing system has been developed. Vertical load and horizontal load are supported by different bearings such as sliding bearing and rubber buffer. The sliding bearing has the function to support the vertical load and isolates the superstructures from the substructures. Using dampers is one of the methods to disperse the inertia force of superstructure, to dissipate the energy and then to control the response displacement. Various dampers including steel damper, liquid damper and viscoelastic damper have been developed. These damping force characteristics are nonlinear and complicated, for example, they depend on loading velocity or loading displacement. They are evaluated and numerically-modeled for dynamic analysis based on cyclic loading tests with each unit. However there are few shake table tests to verify the dynamic response of bride system using dampers.

Based on the above background, shake table tests of isolated bridge model using sliding bearings and dampers were conducted and the numerical analyses were performed to simulate the test results.

Dampers

In this study, shake table tests using two kinds of damper whose characteristics are different are performed. Damper type 1 is oil damper and damper type 2 is bingham damper. The damping force characteristics of both dampers depend on loading velocity. The damping coefficient is large in low velocity and become low in high velocity. The efficiency of energy absorption is high because large damping force performs even in

[1] Research Engineer, Earthquake Engineering Research Team, Public Works Research Institute
[2] Team Leader, ditto

low loading velocity.

Fig.1a) shows the force-velocity characteristics of damper type 1 used in this study. The damping force is generated by flowing thorough the release valve. The trigger opens the release valve to increase the flow volume when the applied force to the valve increases beyond the switching force, 53kN. Thus, the dependency on loading velocity is represented by bilinear. The damping force is defined in Eq.(1). **Fig.1a)** also shows the result of the cyclic loading tests. The damping coefficient C_1 and C_2 are 4000kN/(m/sec) and 180kN/(m/sec) based on the tests. The stroke of damper is ± 120mm.

Fig.1b) shows the characteristics of damper type 2 used in this study and the result of the cyclic loading tests. Bingham plastic fluid is filled in the cylinder of the damper. The fluid doesn’t flow until the applied force to the fluid increases beyond a certain level. When the applied force to the fluid is beyond the certain force the damping force increases according to the loading velocity. The damping force is defined in Eq.(2) based on the tests. The stroke of damper is ±80mm. In this study, 4 dampers are used because the damper type 2 with smaller damping force and stroke than damper type 1 is used. The each characteristic of 4 dampers is almost the same according to loading tests.

$$F = Cv = \begin{cases} 4000v & (v < 0.013) \\ 53 + 180(v - 0.013) & (v > 0.013) \end{cases} \tag{1}$$

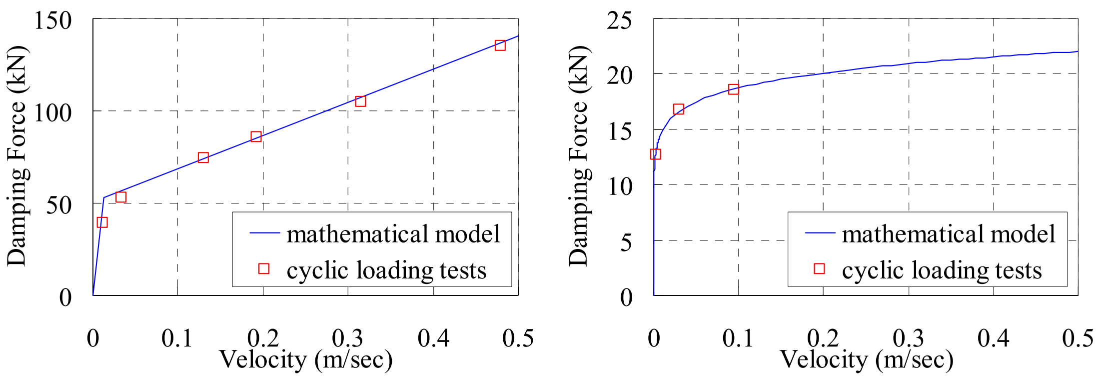
$$F = Cv = 23.6v^{0.1} \tag{2}$$

where

F : damping force (kN)

C : damping coefficient (kN/(m/sec))

v : loading velocity (m/sec)



a) Damper type 1 **b) Damper type 2**

Fig.1 Dependency of loading velocity

Isolated Bridge Model and The Measurement

Fig.2 shows the setup of the bridge model on the shake table. The girder is assembled by H-section steel and counterweight and are vertically supported by four sliding bearings which consist of stainless plate and polytetrafluoroethylene (=PTFE) plate. The frictional coefficient depends on the surface pressure and loading velocity. In these tests condition, the frictional coefficient is about 0.1~0.15 depending on applied surface pressure. They each are on the top of steel columns which are rigidly connected with shake table. The span and width of girder are 5.71m and 1.43m. The frictional force and vertical load acting on sliding bearing are measured by 3-dimensional load cells which underlie every sliding bearing. The response of girder is measured by the acceleration sensors and optical displacement sensors. The acceleration sensor is settled in the midmost shake table to measure the input acceleration.

The weight is different between the bridge models using damper type1 and damper type 2 because the maximum damping forces and damper stroke are different. Using damper type 1, the weights of bridge model (bridge model A) is 283kN. Using damper type 2, the weights of bridge model (bridge model B) is 214kN.

Fig.3a) shows the setup of damper type 1 which is settled parallel with the longitudinal axis between girder and steel column which is rigidly fixed with shake table. The damping force is measured by load cell which is coaxially settled with damper. **Fig.3b)** shows the setup of damper type 2 which is settled parallel with the longitudinal axis between girder and each steel column supporting the girder. The strain gauges are bonded on each damper rod and the damping forces are measured by converting the strains.

Ground Motions and Test Sequence

Fig.4 shows the input acceleration actually observed at JR West Japan Takatori station during the 1995 Hyogo-ken Nanbu Earthquake. NS component of acceleration was inputted parallel with the longitudinal axis. The acceleration was not inputted transversally. **Table1** shows the test cases. Case1~Case4 were performed for bridge model A. Case5~Case8 were performed for bridge model B. The input amplitude

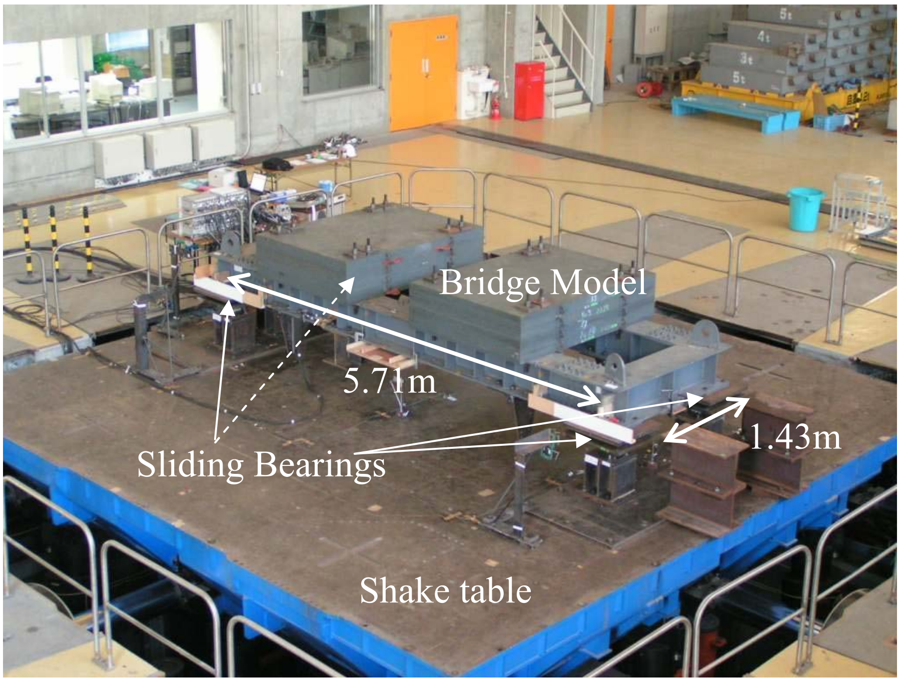
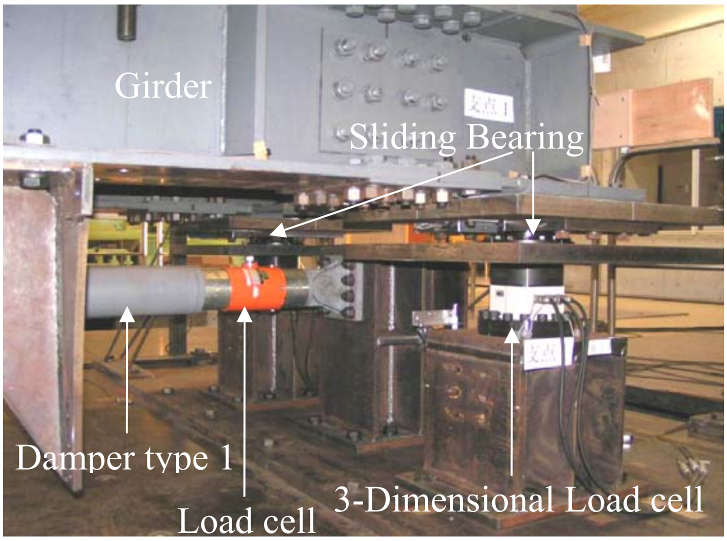
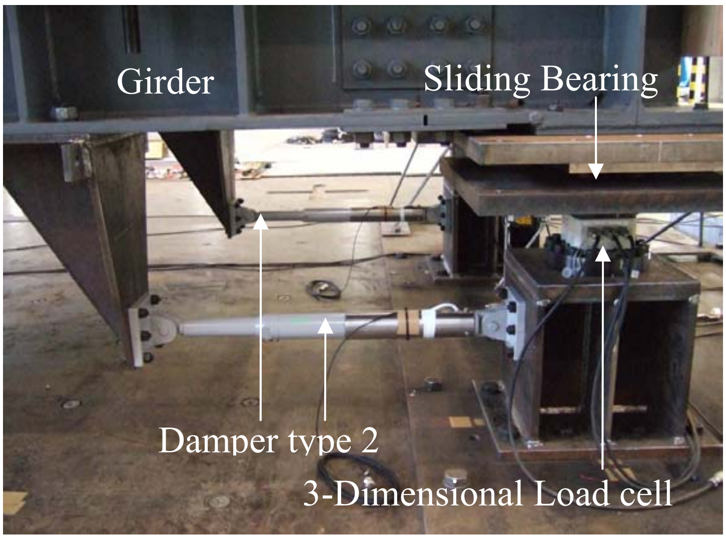


Fig.2 Setup of bridge model

increased gradually in each bridge model because the response of bridge model was unknown before the tests and it was necessary to control the displacement within the damper stroke. Vertical acceleration was inputted in Case4 and in Case8. The purpose is to evaluate the influence of vertical ground motion by comparing the horizontal response in Case3 with Case4 and in Case7 with Case8.



a) Damper on bridge model A



b) Dampers on bridge model B

Fig.3 Setup of damper

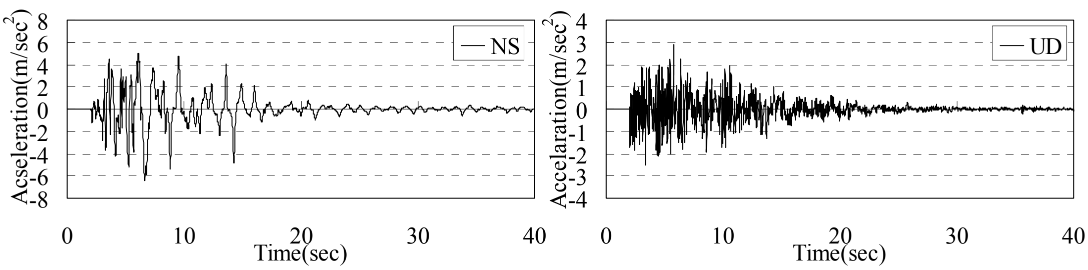


Fig.4 Input acceleration

Dynamic Response of Bridge Model

Table2 shows the maximum responses of the girder displacement, the girder acceleration, the damping force and shake table acceleration. In both bridge models, the larger input acceleration is, the larger the responses of girder and damper are. However the girder acceleration in every case is reduced than the input acceleration.

Fig.5 compares the responses of bridge model A in Case3 with Case4. The frictional force of 4 sliding bearings is summed up in **Fig.5**. The girder acceleration, the damping force and frictional force in Case4 fluctuate according to the frequency of input vertical acceleration. Also, at the time about 4.5sec, the acceleration spikes in Case4. The frictional force of sliding bearings in Case4 increases and decreases according to the variation of the vertical load acting on the sliding bearing. However the displacement of girder in Case4 differs little from the one in Case3.

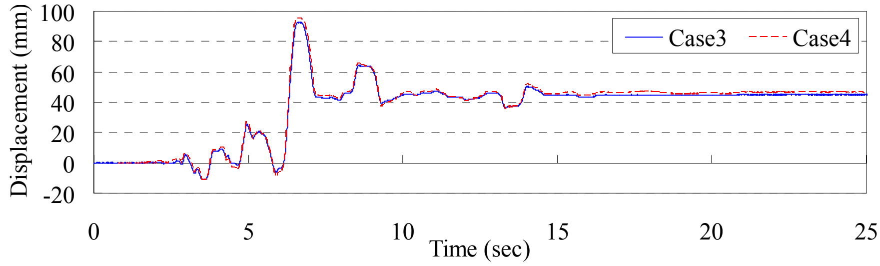
Fig.6 compares the responses of bridge model B in Case7 with Case8. The frictional force of 4 sliding bearings and the damping force of 4 dampers are respectively summed up in **Fig.6**. The characteristic of dynamic responses is almost the same with bridge model A. The test results show that the vertical acceleration doesn't influence the response displacement of girder and damping force for the test conditions conducted in this study.

Table1 Test cases

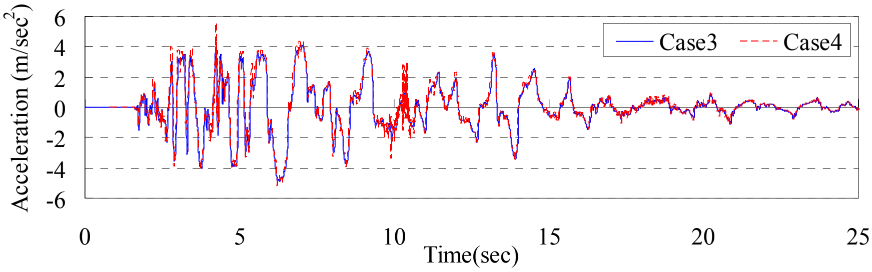
	Bridge Model	Horizontal Direction	Vertical Direction
Case1	A	NS70%	-
Case2	A	NS90%	-
Case3	A	NS100%	-
Case4	A	NS100%	UD100%
Case5	B	NS90%	-
Case6	B	NS95%	-
Case7	B	NS100%	-
Case8	B	NS100%	UD100%

Table2 Maximum response

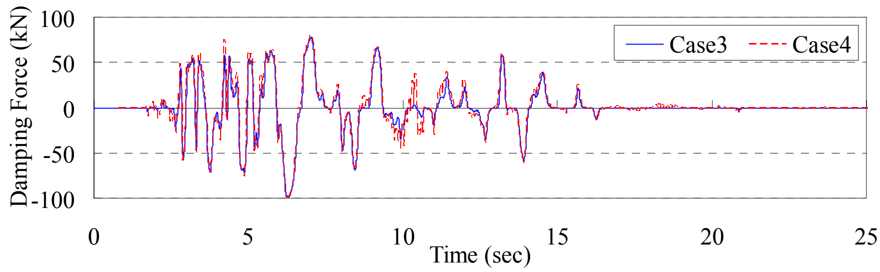
	Input Acceleration (m/sec^2)	Acceleration (m/sec^2)	Displacement (mm)	Damping Force (kN)
Case1	4.62	3.92	29.9	68.2
Case2	6.12	4.52	70.2	87.5
Case3	6.95	4.87	92.7	99.4
Case4	6.72	5.60	95.7	102.5
Case5	6.16	4.89	31.0	71.9
Case6	6.58	5.08	40.8	76.5
Case7	6.99	5.11	55.0	75.8
Case8	6.96	6.01	52.7	76.2



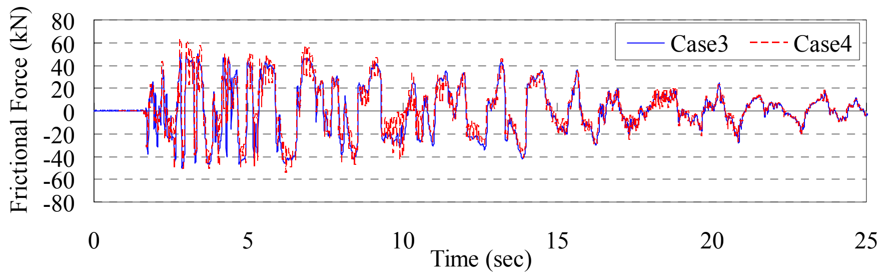
a) Displacement of girder



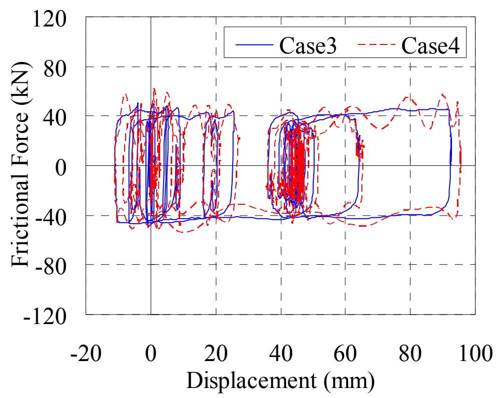
b) Acceleration of girder

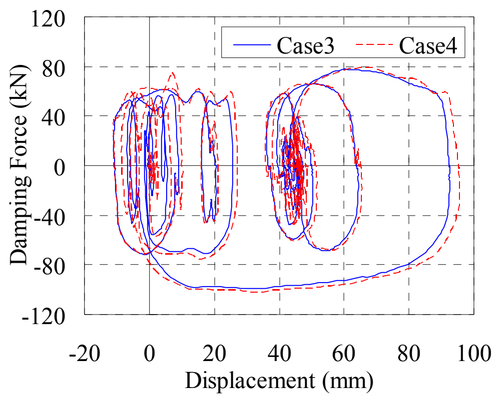


c) Damping force



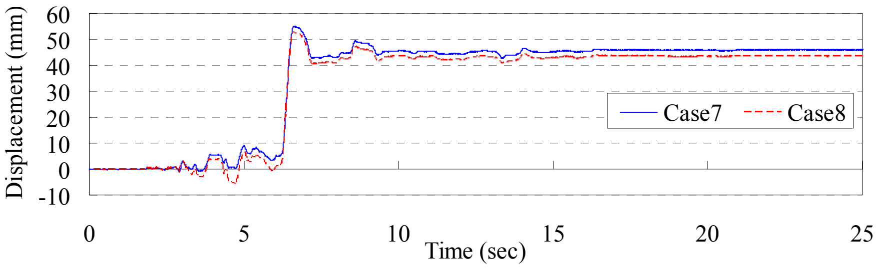
d) Frictional Force of sliding bearings



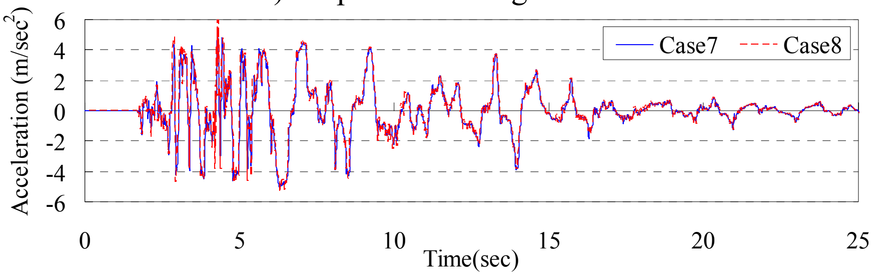


e) Frictional force-displacement hysteresis f) Damping force-displacement hysteresis

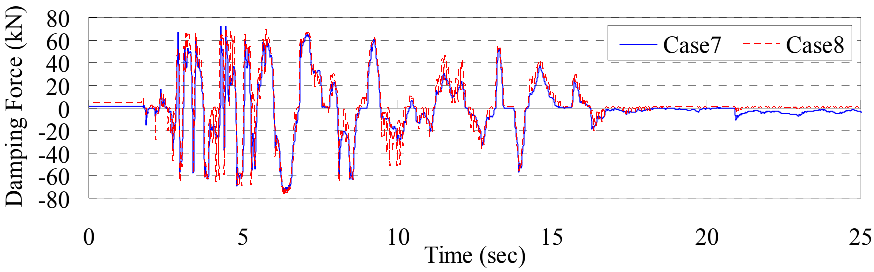
Fig.5 Comparison of the response in Case3(NS100%) with Case4(NS,UD100%)



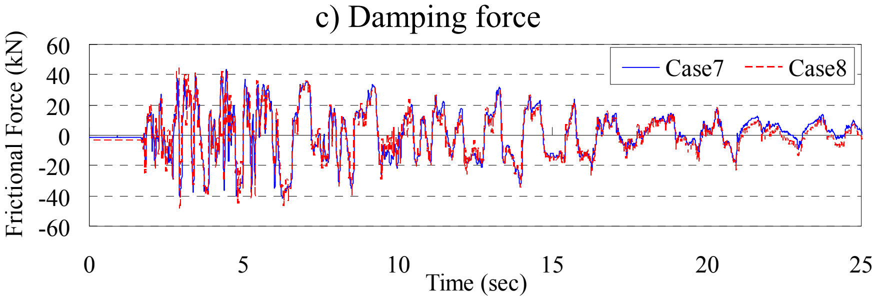
a) Displacement of girder



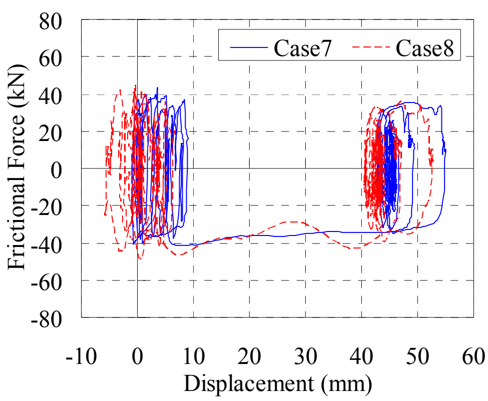
b) Acceleration of girder

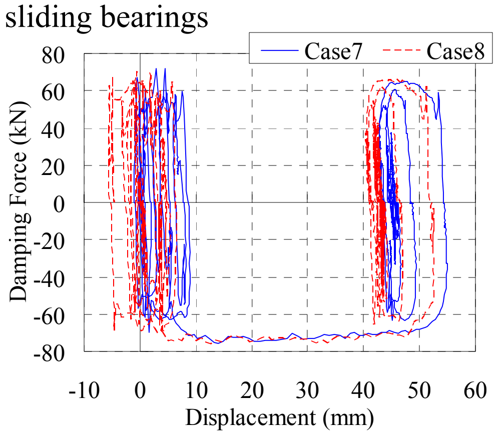


c) Damping force



d) Frictional Force of sliding bearings





e) Frictional force-displacement hysteresis f) Damping force-displacement hysteresis

Fig.6 Comparison of the response in Case7(NS100%) with Case8(NS,UD100%)

Analytical Simulation and Damping Effect

Nonlinear dynamic analyses are performed to simulate the behaviors of the bridge models. The bridge models are idealized with one mass system as shown in **Fig.7**. The frictional coefficient of sliding bearings depends on the surface pressure and loading velocity. However, in this study, 4 sliding bearings are collectively idealized with simple rigid plastic spring element up to 40kN and 30kN in the bridge model A and B based on the observed averagely frictional force. The damper in bridge model A is idealized with the nonlinear damping element represented as Eq.(1). 4 dampers in bridge model B are collectively idealized with simple rigid plastic spring element up to 70kN because there isn't the damping element represented as Eq.(2) in used analysis software and the damping force characteristic is similar to sliding bearing.

The viscous damping of the system is assumed to be 0. The Newmark β method (β=1/4) is used. Also, the analyses for the cases where vertical acceleration is inputted are not performed because the test results are almost the same regardless of whether vertical acceleration is inputted.

Fig.8~Fig.10 show the comparison of the displacement of girder, the frictional force and damping force for the tests of bridge model A with the analyses. The displacement amplitudes of analyses are smaller than the tests. The larger the input acceleration is, the displacement is simulated more accurately. The residual displacements are not simulated well in every case. However the frictional forces and damping forces are almost simulated well in every case.

Similarly, **Fig.11~Fig.13** show the comparison about bridge model B. The displacement amplitudes of analyses are smaller than the tests and the timing to slide is not simulated well. The larger the input acceleration is, the maximum displacement is simulated more accurately. The bridge model wiggled in the tests because the damping force is low in low loading velocity. However, because the sliding bearings and dampers are idealized with simple rigid plastic spring elements the dynamic responses are not simulated well for this point.

The analytical estimation of the damping effect is performed for Case3. **Fig.14** shows the result of analytical simulation for the bridge model supported by only sliding bearings without damper. The displacement is about six times the displacement of Case3. The analysis result shows that the damper plays the important role to control the displacement.

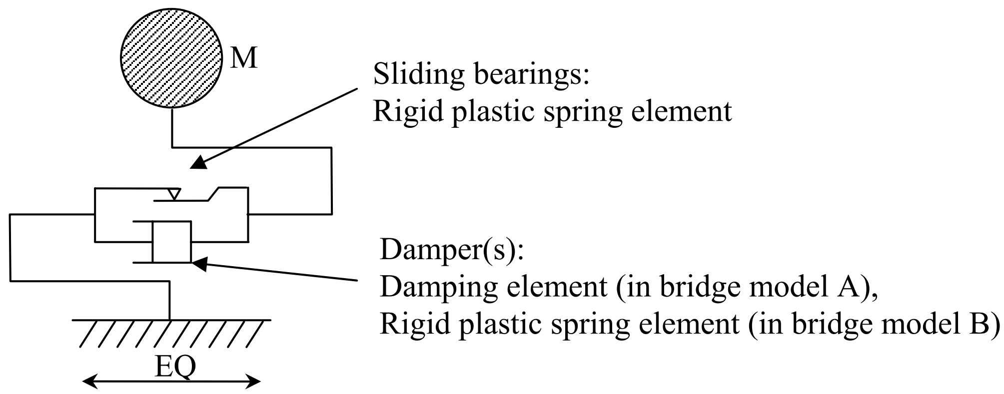
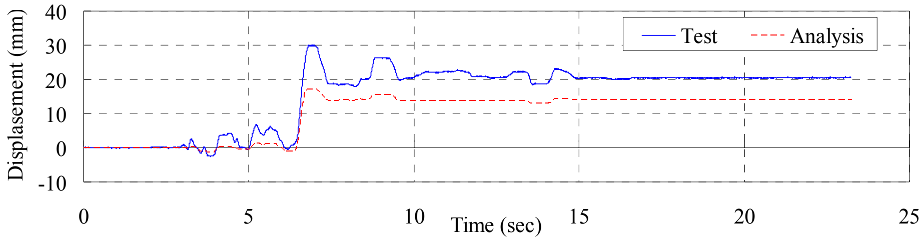
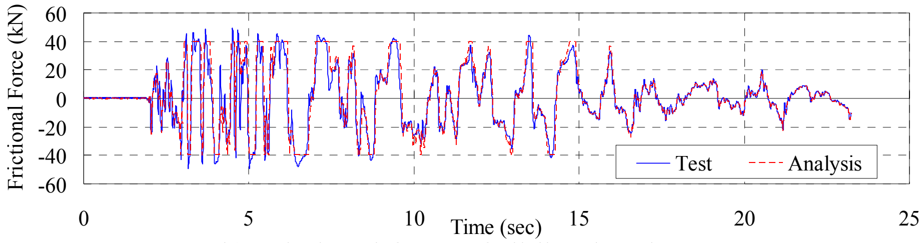


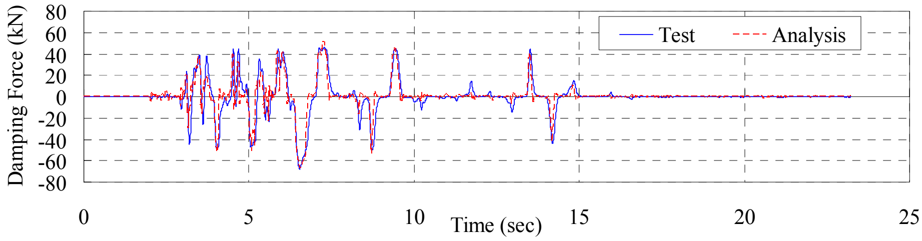
Fig.7 Analytical model



a) Displacement of girder

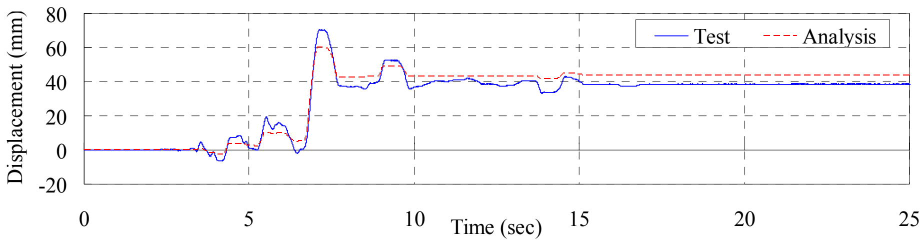


b) Frictional force of sliding bearings

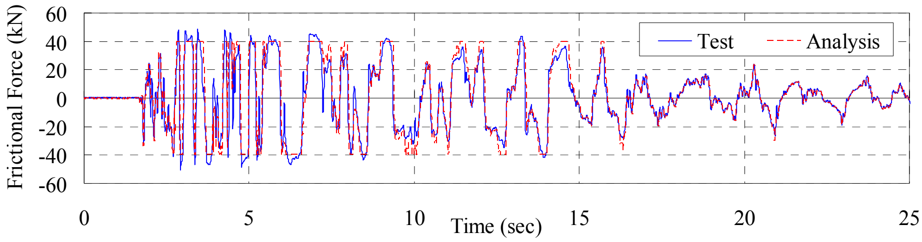


c) Damping force

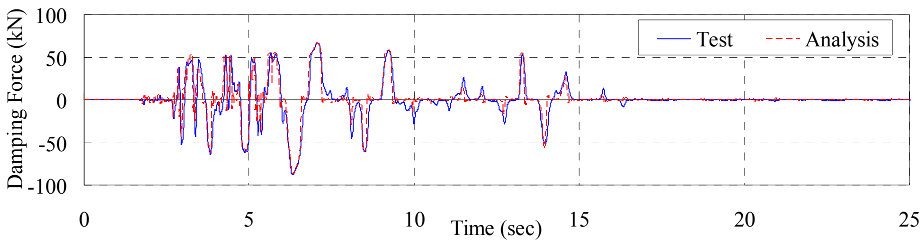
Fig.8 Analytical simulation in Case1(NS70%)



a) Displacement of girder

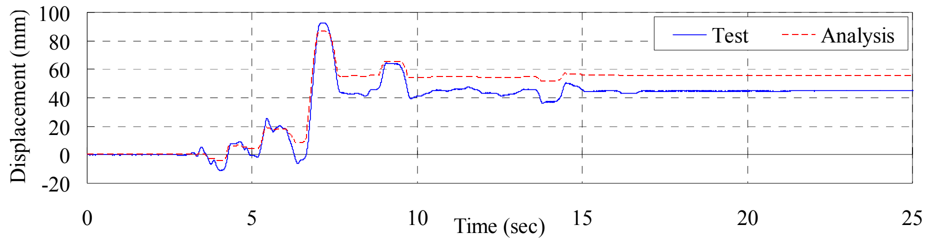


b) Frictional force of sliding bearings

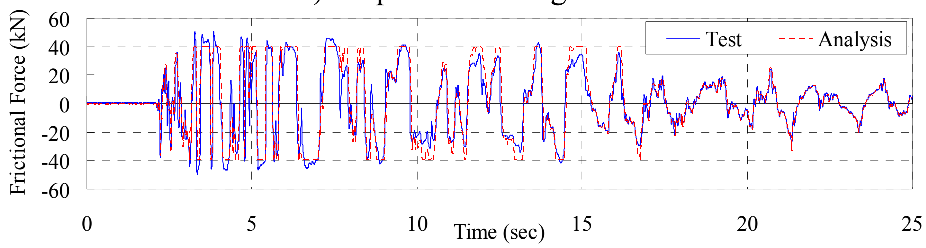


c) Damping force

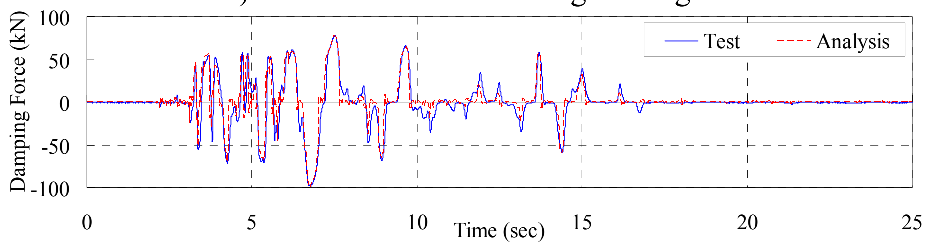
Fig.9 Analytical simulation in Case2(NS90%)



a) Displacement of girder

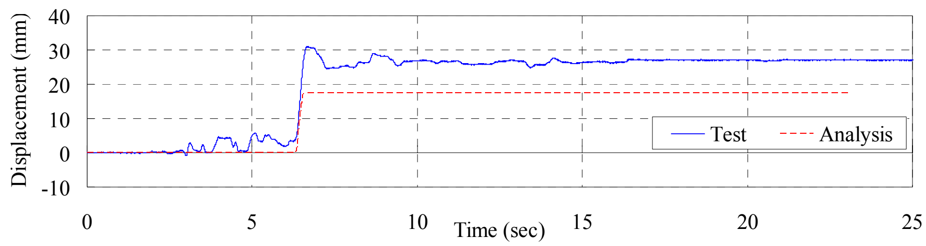


b) Frictional force of sliding bearings

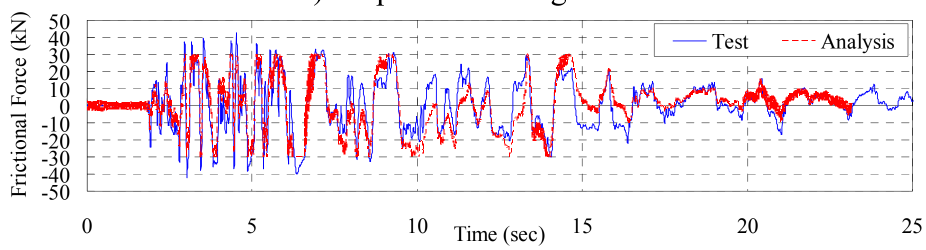


c) Damping force

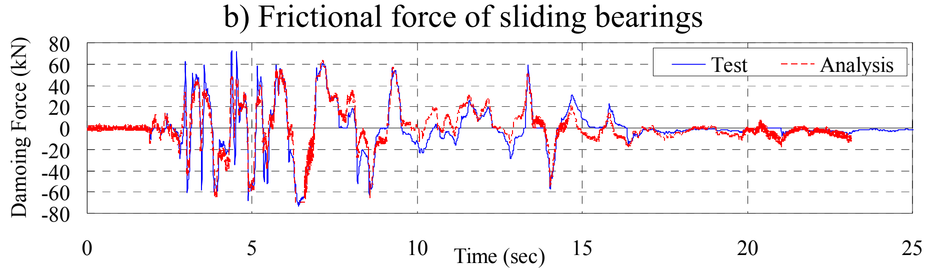
Fig.10 Analytical simulation in Case3(NS100%)



a) Displacement of girder

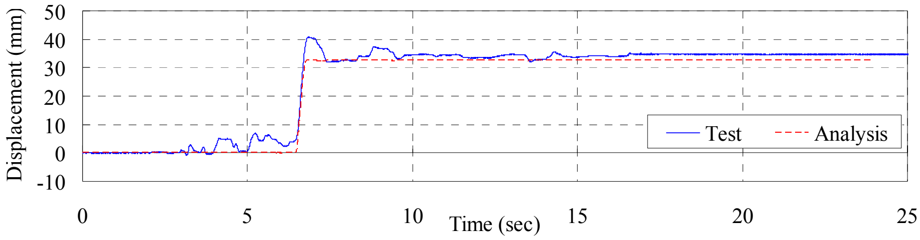


b) Frictional force of sliding bearings

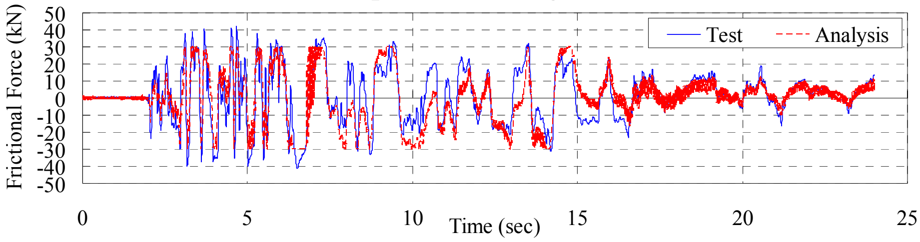


c) Damping force

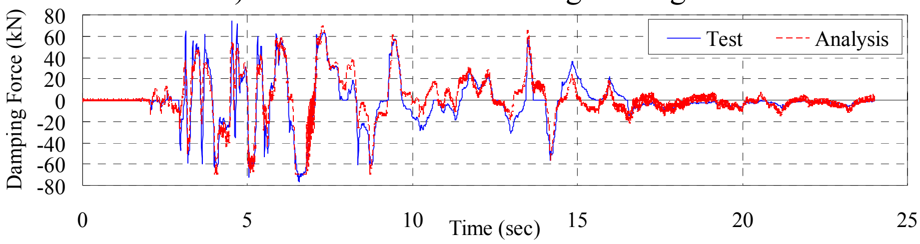
Fig.11 Analytical simulation in Case5(NS90%)



a) Displacement of girder

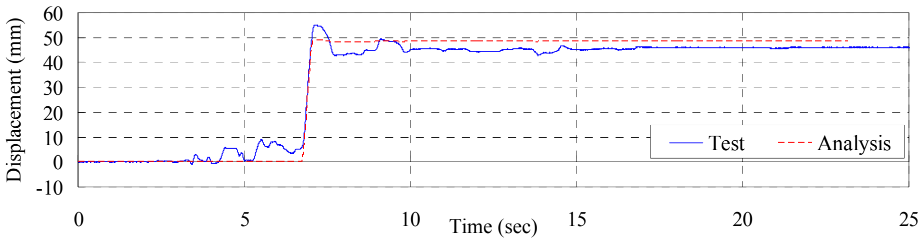


b) Frictional force of sliding bearings

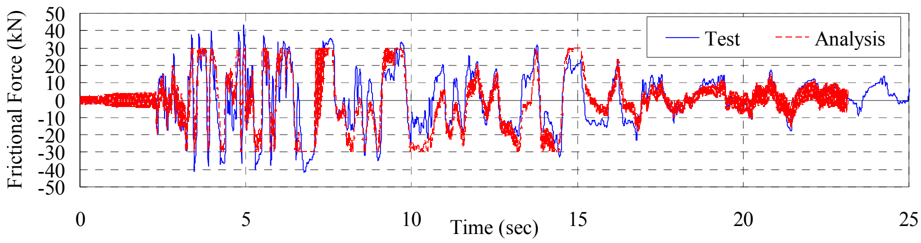


c) Damping force

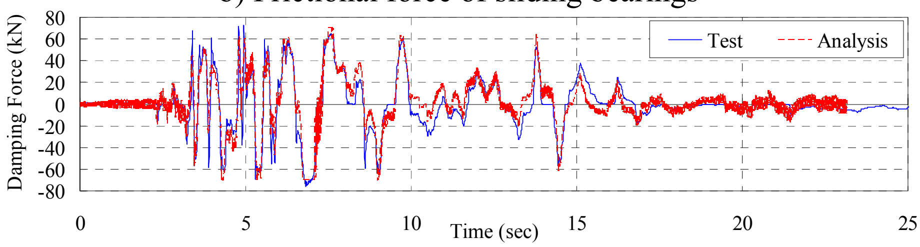
Fig.12 Analytical simulation in Case6(NS95%)



a) Displacement of girder



b) Frictional force of sliding bearings



c) Damping force

Fig.13 Analytical simulation in Case7(NS100%)

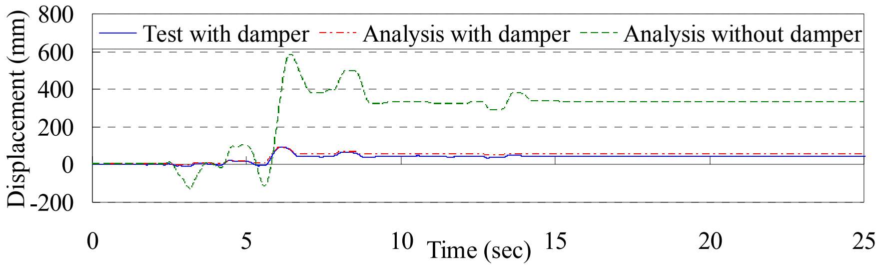


Fig.14 Damping effect for displacement

Conclusion

To investigate the seismic behavior of isolated bridge model using sliding bearings and dampers, a series of shake table tests and analyses have been conducted. Nonlinear dynamic analyses using simple mass model are performed to simulate the behaviors of the each bridge model. The result shows that it is possible to simulate the seismic responses approximately.

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Takehiko Himeno and Shigeki Unjoh (2003). "Consideration on the modeling method for the frictional characteristics of the sliding bearings" Journal of Earthquake Engineering, JSCE, Vol.27