

# REAL-TIME HYBRID TESTING OF LAMINATED RUBBER DAMPERS FOR SEISMIC RETROFIT OF BRIDGES

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## ABSTRACT

Experimental investigation of laminated rubber dampers by means of real-time hybrid testing of scaled specimens is presented. Purpose of the real-time hybrid testing is to evaluate the dynamic response control performance with experimentally simulated seismic response of a numerical model of a bridge to which the laminated rubber damper is implemented. In the real-time hybrid testing, the structure to be tested is divided into one or more experimental and computational substructures with actuators providing the interface between them. Since the laminated rubber dampers can exhibit velocity-dependent behavior due to viscosity and other dynamic properties of rubber material, real-time loading is indispensable in testing the performance of the device under realistic test condition for the damper specimens that reflects the loading rate effect. The real-time hybrid experimental system is implemented using the concept of velocity-based loading control, and the obtained test results are compared with those obtained with conventional hybrid loading tests.

## INTRODUCTION

In order to ensure required seismic performance of long-span bridges, installation of additional energy dissipation devices, or dampers, is expected to be an effective retrofit measure. Energy dissipation devices for this purpose are required to have large stroke capacity and ability to generate high damping force, while pursuing economical efficiency to be achieved by reasonable manufacturing and maintenance cost. It is quite difficult to satisfy these physical and cost requirements with conventional types of dampers, such as viscous-type, inelastic-type and friction-type devices. To overcome this difficulty, the laminated rubber damper is newly developed as a seismic response control device for bridges with larger stroke and high damping force capacities, taking advantage of high damping rubber material which can absorb large amount of energy without axial force, developed by rubber manufacturers in Japan in recent years (Iemura et al, 2008).

In this paper, experimental investigation of laminated rubber dampers by means of loading tests of scaled specimens is described. The verification test program for the laminated rubber dampers consists of two types of tests: cyclic loading tests to characterize the damper's performance with respect to equivalent stiffness, damping ratio of and their strain dependence, and the hybrid earthquake loading tests to evaluate the dynamic response control performance with experimentally simulated seismic response of a numerical model of a bridge to which the laminated rubber damper is implemented. In the hybrid experimentation, the structure to be

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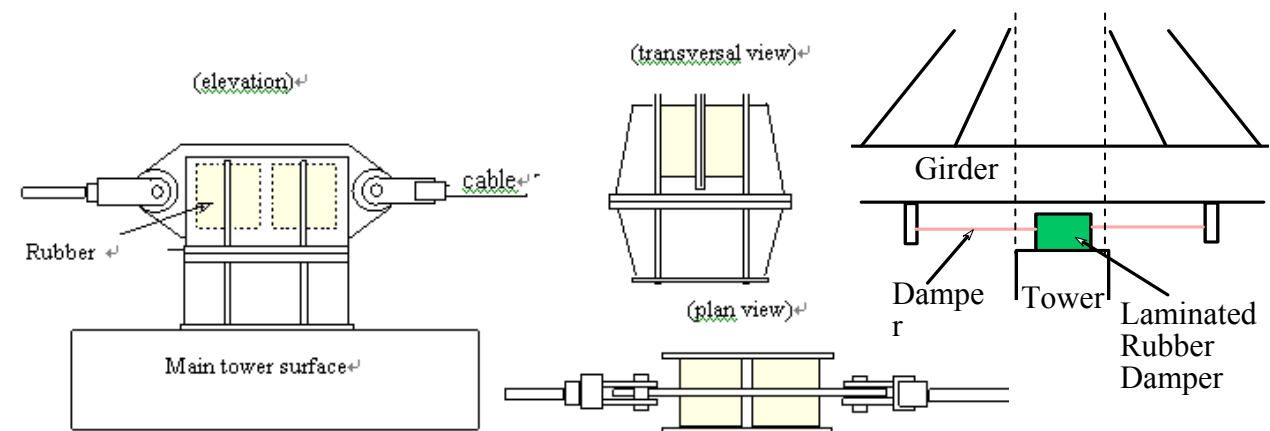
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tested is divided into one or more experimental and computational substructures with actuators providing the interface between them. Thus, hybrid simulation provides information of the entire structure without the need of testing the whole system.

Since the laminated rubber dampers can exhibit velocity-dependent behavior due to viscosity and other dynamic properties of rubber material, real-time loading is indispensable in testing the performance of the device under realistic test condition for the damper specimens that reflects the loading rate effect. For this purpose, a real-time hybrid loading test system was developed for the present experimental verification test program. Implementation of the real-time hybrid experimental system using the concept of velocity-based loading control (Iemura et al, 2005) is also described in this paper, and the obtained test results are compared with those obtained with conventional hybrid loading tests.

### LAMINATED RUBBER DAMPER AND TEST SPECIMEN

The layout of the laminated rubber damper used for the large cable stayed bridge is shown in Figure 1. Four laminated high damping rubber (HDR-S) blocks are placed inside a casing rigidly



**Fig. 1. Overview of laminated rubber damper for bridge**

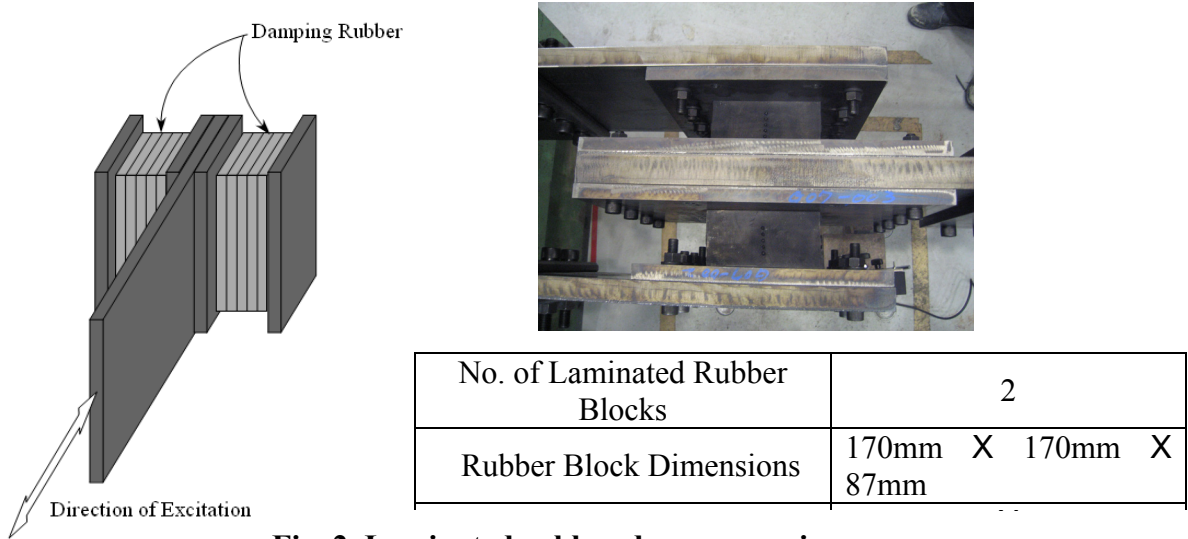
connected to the bridge tower. As the center plate connected to the main bridge girder with cables moves in the horizontal longitudinal direction, the laminated rubber blocks are subjected to shear deformation while the damping force is generated by the shear stress in the laminated rubber. Cable connection is assumed to avoid torsional and flexural stresses that can be induced in case the damper is directly connected to the girder.

The laminated rubber damper test specimen is shown in Figure 2. The dimensions of the specimen suggest that the displacement range of +/- 52.5mm corresponds to 175% shear strain, and load level of approximately 95kN, considering that the 1.2 N/mm<sup>2</sup> class shear modulus of the rubber used in the specimen.

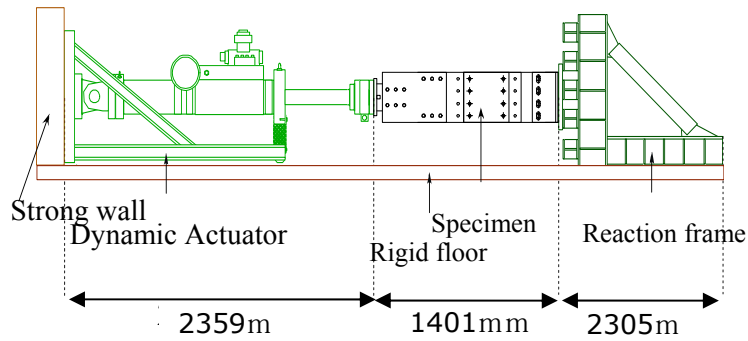
### CYCLIC LOADING TEST

Figure 3 shows the test setup for the loading test of the laminated rubber damper specimen. Figure 4 shows the hysteresis loops obtained by the cyclic loading tests. Figures 5 shows equivalent stiffness and damping ratio for various loading rates shear strains obtained as the

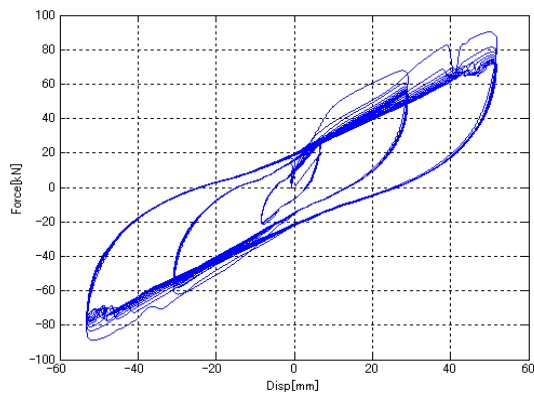
cyclic loading test with different combinations of loading frequencies and displacement amplitudes. Although decrease of equivalent stiffness and equivalent damping ratio for larger shear strain levels can be seen in the figure, the test result indicates laminated rubber damper's stable behaviour and efficient performance as an energy dissipation device.



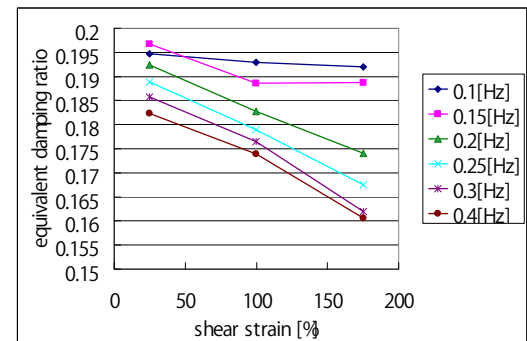
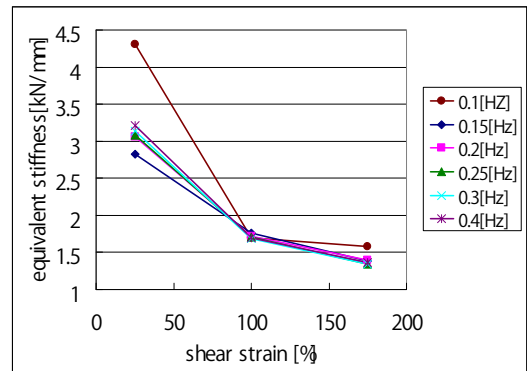
**Fig. 2. Laminated rubber damper specimen**



**Fig 3. Test setup**



**Fig. 4. Hysteretic behavior of laminated rubber damper**



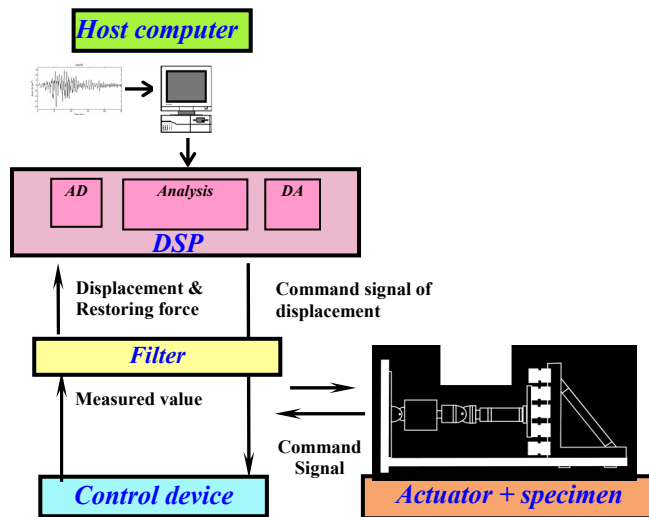
**Fig. 5. Equivalent stiffness and damping ratio of laminated rubber damper**

## REAL-TIME HYBRID TEST

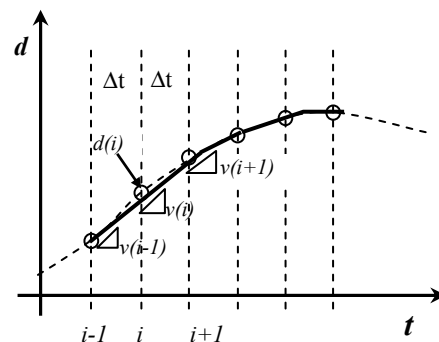
Since the result of the cyclic loading test does not directly correspond to the seismic response of the structural system to be evaluated, and also the behavior of the rubber bearing is measured only under unrealistic stationary cyclic loading conditions, the on-line pseudo-dynamic test, or hybrid loading test can be employed in the validation of the laminated rubber damper. The conventional pseudo-dynamic test is an experimental method in which experimental loading and numerical computation are conducted simultaneously, so that the restoring force of structural component is measured by on-line instrumentation during loading tests of the component, and the dynamic response of the structural system is evaluated by numerical computation. In this regard, the pseudo-dynamic test incorporating the substructure technique is referred to as the substructure hybrid loading test. Furthermore, the hybrid loading test method on the basis of the real-time test, where the input excitation is imposed in a high-rate in such a way that it simulates the actual earthquake motion in real-time is used in this study. This type of test method is referred to as the real-time hybrid loading test method. Figure 6 schematically shows the experimental framework of the real-time hybrid loading test which consists of the elements of actuator loading with control of displacement, numerical computation with computer and instrumentation systems.

The test starts when the earthquake record is input into the numerical substructure at time  $i$ , and the displacements at time  $i+1$  are calculated numerically using a direct step-by-step integration strategy and imposed into the experimental substructure through actuators. The restoring forces due to these displacements are measured and provided to the computational substructure model. Finally, the velocities and accelerations are calculated in the numerical substructure and the loop is repeated until the whole earthquake record is processed. Therefore, the test will last the total duration of the input motion.

In a displacement-controlled real-time test, the signals have to be imposed from the numerical to the experimental substructure continuously. However, in the actual test due to both, the inherent delay in the response of the actuator and the delay in the data transfer between the computational

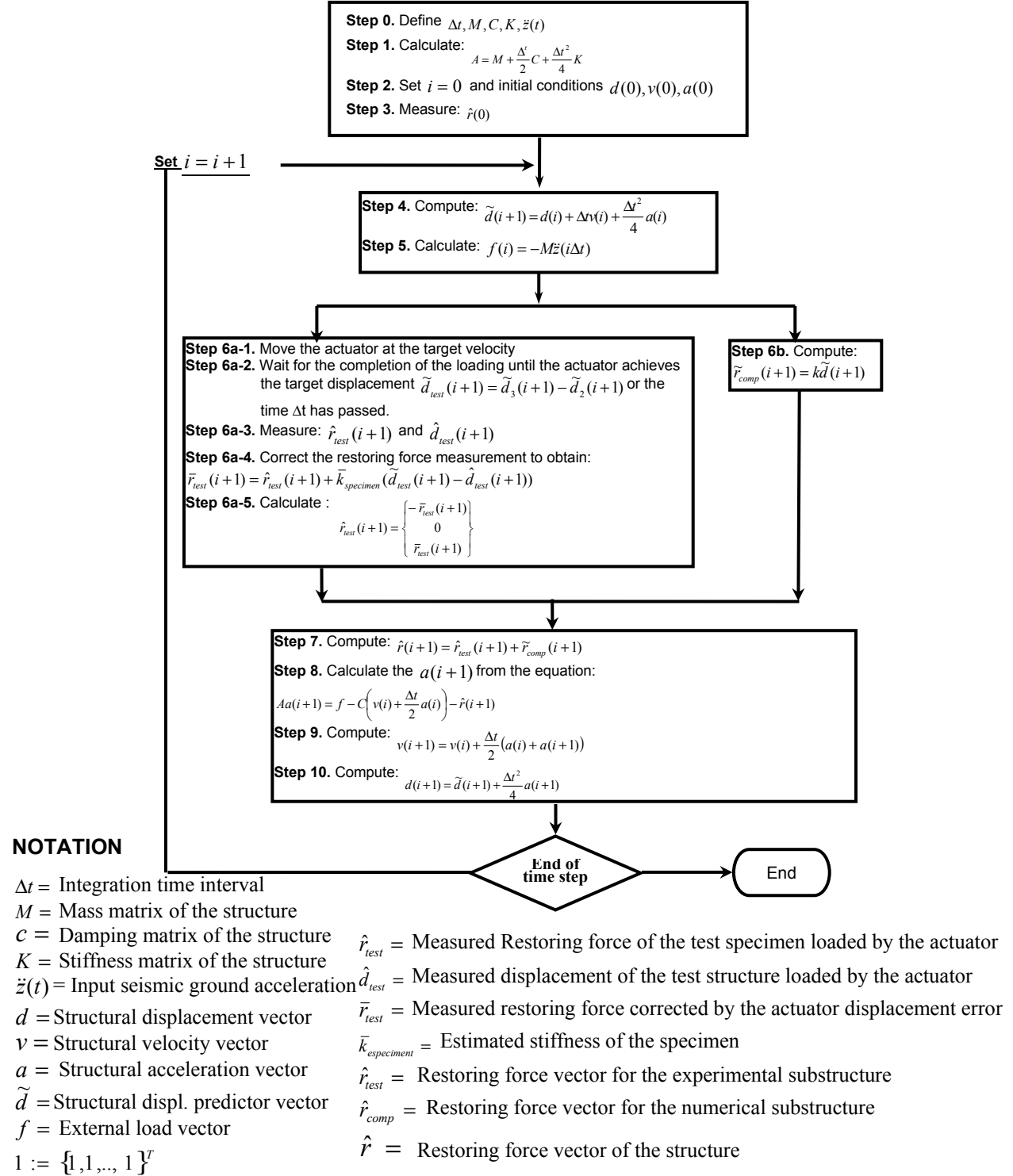


**Fig. 6. Experimental framework for real-time hybrid loading test**



**Fig. 7. Concept of velocity-based loading**

hardware, the control signal is not properly achieved in real-time. Thus, sophisticated control and extremely fast communication among all components of the test are required. These aspects are still major issues to be enhanced in real time experimentation. In parallel with the methods to compensate the delay of the actuator, several algorithm and control schemes have been developed.



**Fig. 8. Flow chart of the real time hybrid test algorithm**

Most of the displacement-controlled approaches are based in the extrapolation and interpolation of the actuator displacements; in this work, a different approach characterized by the velocity-based loading was adopted. This test control algorithm allows flexibility to assign more time to complete critical steps depending on the complexity of the test, and at the same time, optimizes the computational resources, which consisted of a single host computer and a single DSP processor.

In the velocity dependent algorithm, at the time step  $t_i$  the velocity  $v_i$  is calculated together with the displacement  $d_{i+1}$ . The displacement command signal is linearly changed to move the actuator at the velocity  $v_i$  and this velocity is maintained during the time step interval  $\Delta t$ . Once the iteration is completed, time  $t_{i+1}$ , the restoring force is measured and the next target displacement and the velocity,  $v_{i+1}$ , at the current step are calculated, see Figure 7. Finally the command signal is updated to  $v_{i+1}$  while keeping the actuator on movement. This procedure is repeated at each time step. The flowchart of the real-time hybrid loading test algorithm which includes the operator splitting method as the time integration scheme is shown in Figure 8.

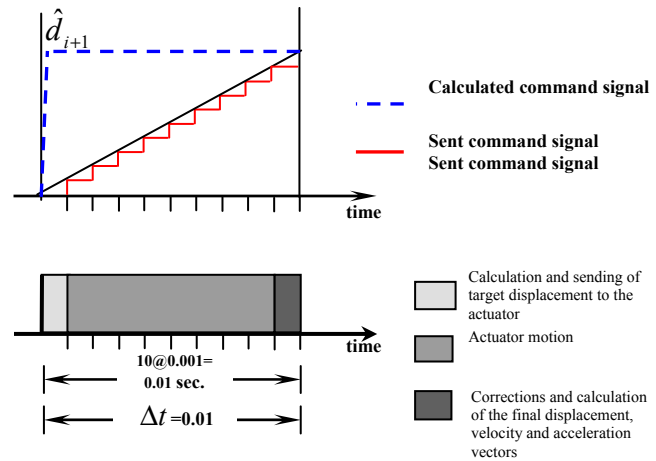
### CONTROL ALGORITHM FOR REAL-TIME IMPLEMENTATION

The signal displacements are imposed continuously to the actuator each millisecond (ms) to achieve smooth motion. The integration time step,  $\Delta t$ , was set equal to 0.01 sec (10ms). Considering these conditions, the calculations in one time integration step were divided in 10 sub steps (each millisecond) as follows (Figure 9):

**1st ms:** The target displacement,  $\hat{d}_{i+1}$ , is calculated and the signal is imposed to the actuator.

**2th-9th ms:** In parallel with the sending of partial signals, the program waits for the achievement of the target displacement by the actuator. Even in the case the target displacement is not achieved during this time, the actuator keeps moving until the desired position at the velocity of the current step. The reading of the displacement and restoring forces is done until the 9th ms. Thus, the obtained displacement is close the target one.

**10th ms:** The final calculation of the displacement, velocity and acceleration vectors is performed while the actuator keeps moving with the velocity imposed in the 1st ms.

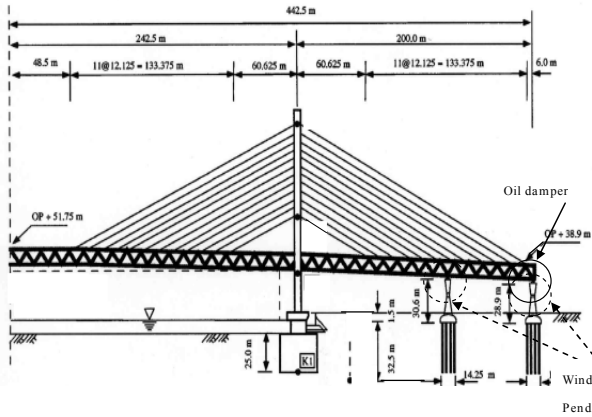


**Fig. 9. Control concept**

### ASSUMED STRUCTURE IN SIMULATION AND ACTUATOR DELAY

The structure to be used in the present study analyzed is the Higashi Kobe Bridge, for which structural upgrading project for seismic retrofitting using the proposed laminated rubber damper was undergoing at the time of the experiment. Dimensions of the Higashi Kobe Bridge are shown in Figure 10 and Table 1. The end of the girder is connected to the viscous damper and

wind and pendel bearings. The viscous oil type damper was designed at the time of construction so as to obtain the 2% damping ratio for the longitudinal vibration of the girder, which later found not enough for large magnitude inter-plate earthquake ground motion.

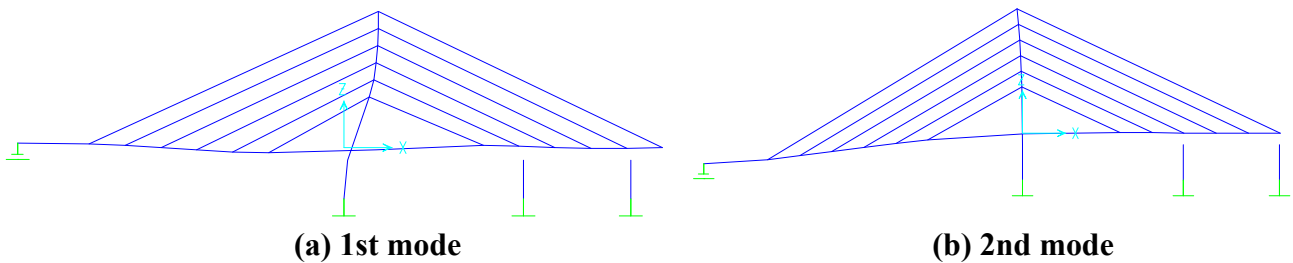


**Fig. 10. Higashi Kobe Bridge**

**Table 1. Dimension of Higashi Kobe Bridge**

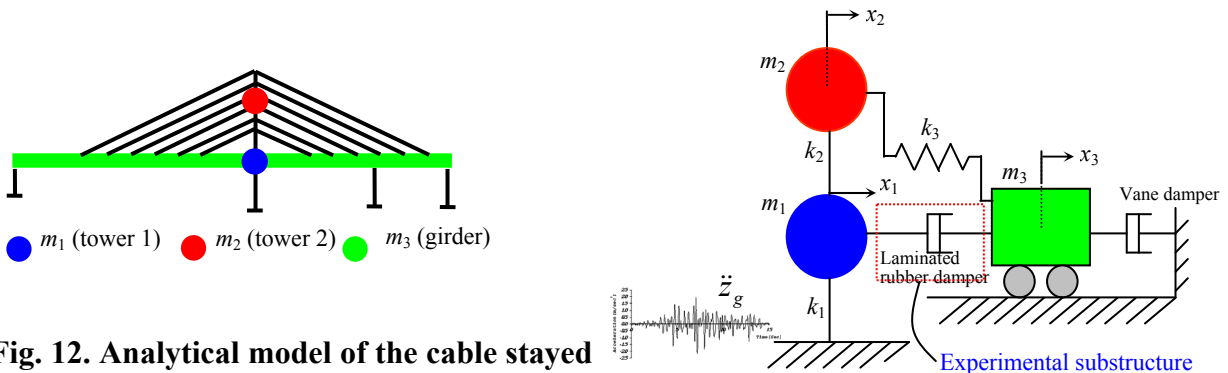
Type	3 span continuous cable stayed bridge
Type of Highway Group	2 Class 1
Length	200+485+200=885m
Width	13.5 x 2 decks
Main Tower	High 146.5m
Main Girder	Warren Truss (High 9m)
Cables	Harp type (12 parallel)
Weight	Main girder 14,100
	Main tower 7,900
	Cables 1,300 Total 27,400
	Abutment 1,700
	Others 2,400

The 1st and the 2nd modes of the bridge calculated with a numerical model are shown in Figure 11. The first and second modes correspond to longitudinal, and lateral motion of the main girder, respectively. These two modes are well separated, and the laminated rubber damper is intended to reduce the longitudinal dynamic response which is regarded as a result of mainly the contribution of the first mode.



**Fig. 11. Natural modes of the cable stayed bridge**

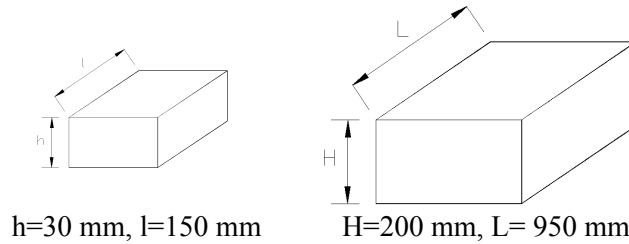
For the real-time hybrid loading test, the bridge including the laminated rubber damper connected to the tower and the girder is reduced to 3-degree-of-freedom model to execute fast calculation of the response for fast loading test of the damper, as shown in Figure 12. The masses



**Fig. 12. Analytical model of the cable stayed bridge to be applied**

$m_1$  and  $m_2$  represent the lower and upper part of the tower and the mass  $m_3$  represents the girder, respectively. The springs  $k_1$ ,  $k_2$  and  $k_3$  represent the flexural stiffness of the tower and the axial stiffness of cables, respectively. The inelastic restoring force of the damper from the test is inserted between  $m_1$  and  $m_3$ . The natural period of the 1st mode of the 3-degree-of-freedom model is 4.2 sec.

The dimensions of the laminated rubber dampers that are assumed to be applied for the bridge, along with the laminated damper test specimen, are shown in Figure 13. It implies that the specimen was scaled by the following factors: the elevation scale factor is  $200\text{mm}/30\text{mm}=6.667$  and plan scale factor equals to  $950\text{mm}/150\text{mm}=6.333$ . Those factors are considered in the numerical integration algorithms in the test control code.



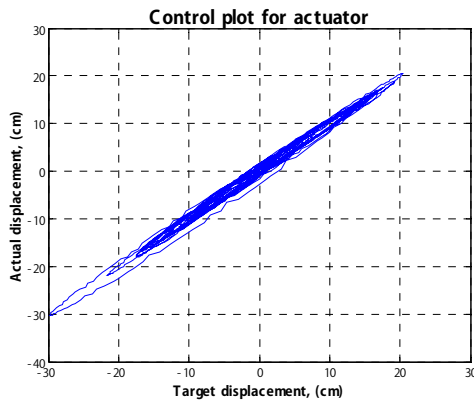
**Fig. 13. Dimensions of test specimen and prototype laminated rubber damper**

The equation of motion, solved by the Operator Splitting Method (OSM) is:

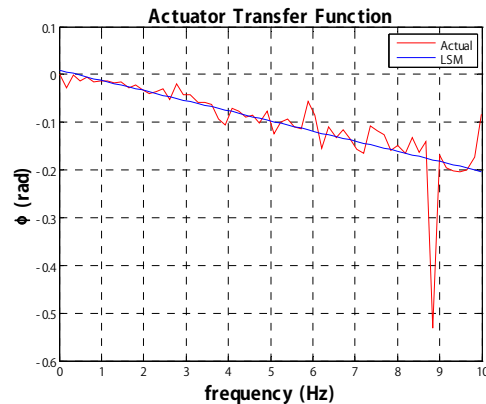
$$Ma + R_N(d, v) + R_E(d, v) = F \quad \dots (1)$$

where  $d$  is the vector of nodal displacements,  $v$  is the vector of nodal velocities,  $a$  is the vector of nodal accelerations,  $R_N$  is the restoring force of the numerical substructure and  $R_E$  is the restoring force of the experimental substructure.

In considering the test control algorithm, the dynamic response of the actuator to the command signal was obtained as shown in Figure 14 and the delay time of the actuator response was calculated. In Figure 14b, the red line indicates the actual variation of the phase that follows a constant decrement tendency approximated by a straight line, obtained by least square method (blue line), in the frequency range of interest, taken between 0.001 to 10.000 Hz. The delay time of the actuator can be calculated by the value of delay phase angle of 0.094 rad for  $f=5$  Hz, as  $\delta=0.094/\pi=0.030$  sec.



**(a) Command signal vs. actuator displacement**



**(b) Phase delay vs. input signal frequency**

**Fig. 14. Dynamics of actuator**



The reaction force increment between predictor and corrector displacements is assumed related linearly to the difference of two displacements by a linear stiffness. Herein, the correction to the actuator displacement error, including the effect of actuator delay time, is given by:

$$\bar{r}_{test}(i+1) = \hat{r}_{test}(i+1) + \bar{k}_{specimen}(\tilde{d}_{test}(i+1) - \hat{d}_{test}(i+1)) \quad \dots (2)$$

In equation (2),  $\hat{r}_{test}$  is the measured force,  $\bar{k}$  is the elastic stiffness of the substructure (laminated rubber specimen),  $\tilde{d}_{test}$  is the displacement calculated analytically,  $\hat{d}_{test}$  is the measured (obtained) displacement, and  $\bar{r}_{test}$  is the modified force that will be incorporated to the numerical substructure.

## TEST RESULTS

The hybrid loading tests of laminated rubber dampers were conducted. For comparison purposes, the conventional hybrid loading tests with slow loading rate were carried out, in addition to the real-time hybrid loading test to test the laminated rubber damper.

The response obtained with the real-time hybrid loading test using the Nihonkai-chubu earthquake, corresponding to level-1 earthquake with amplitude scaled to 50% is shown in Figure 15a. There is a reasonable concordance between the two sets of results: the obtained with the real-time system and those from the conventional hybrid loading test. Figure 15b shows the corresponding comparison of the hysteresis loops. It is observed that the hysteresis loops are stable and effectively absorbing the vibration energy. For these tests, the maximum difference in displacements is 5% and the maximum one in force is 5%. For the type of laminated rubber damper, the difference is considered to be due to the effect of the loading rates. In conventional hybrid loading tests, the restoring force characteristics can be measured to be lower than the actual performance, which is the issue that can be avoided by the use of real-time tests.

The effectiveness of the additional damping can be evaluated by comparison of the displacement response of the bridge with laminated rubber dampers and without these devices. Figure 16 shows the relative displacement response between the girder and the horizontal beam of the

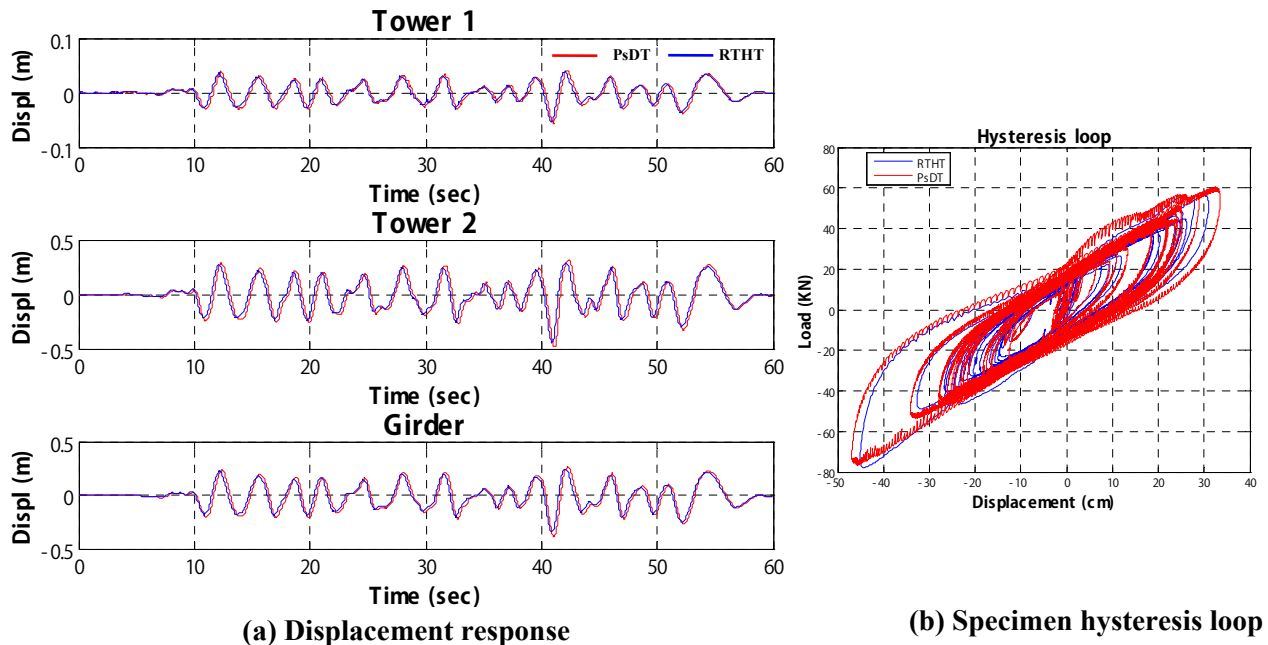
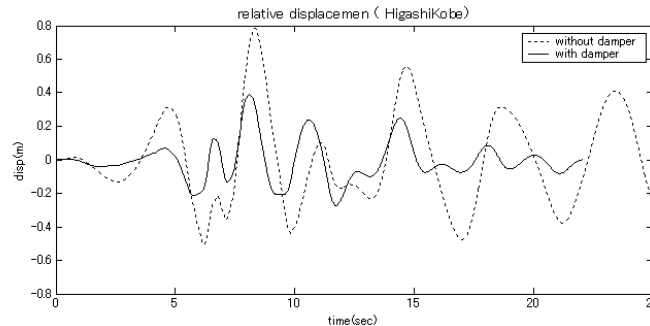


Fig. 15. Test Result: comparison of conventional and real-time hybrid loading tests

tower with and without the damper, for the case of the earthquake ground motion recorded at the site during the Hyogo-ken Nanbu earthquake. The response for the case without damper is obtained by numerical computation, and that for the case with the damper is the result of conventional hybrid loading test, converted into the prototype dimensions. The figure illustrates the effect of the application of laminated rubber damper to the bridge in reducing the seismic response.



**Fig. 16. Test result: effect of laminated rubber damper application**

## CONCLUSIONS

Experimental investigation of laminated rubber dampers by means of cyclic loading tests and hybrid loading test of scaled specimens is described. The hybrid earthquake loading tests to evaluate the dynamic response control performance with experimentally simulated seismic response of a numerical model of a bridge to which the laminated rubber damper is implemented. The finding described in this paper is summarized as follows:

1. In order to evaluate the behavior of laminated rubber dampers that can show strain rate dependence, a real-time hybrid loading test system was developed for the experimental verification tests. The real-time hybrid experimental system was implemented using the concept of velocity-based loading control, which allowed the simplification of the coding framework.

2. Real-time and conventional hybrid loading tests of laminated rubber dampers, simulating dynamic response of a long-span steel cable stayed bridge with the laminated rubber damper were conducted. Comparison of the obtained test results of the real-time hybrid loading test and those of conventional hybrid loading tests shows the difference that reflects the loading rate effect on the laminated rubber damper specimen, suggesting the necessity of real-time testing in the evaluation of the performance of laminated rubber dampers .

3. The test results showing the simulated seismic responses of the bridges with and without the damper show that the laminated rubber damper is effective in significantly reducing the seismic response of the bridges.

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