Hybrid simulation for seismic performance assessment of a cable-stayed bridge retrofitted with laminated high damping rubber dampers

15 WCEE
LISBOA 2012

A. Igarashi
Kyoto University, Japan

H. Iemura
Kinki Polytechnic College, Japan

M. Yoshida
Kawakin Core-Tech Co. Ltd., Japan

F. Taya
West Japan Railway Co., Japan

SUMMARY:
Applicability of the hybrid simulation technique as a measure to evaluate seismic performance of a cable-stayed bridge retrofitted with laminated high damping rubber dampers is investigated. The experimental substructure is a laminated high damping rubber damper specimen of 1/4 scale to the prototype device, consisting of four laminated rubber assemblies, connecting and supporting plates, and a dynamic MDOF model of the cable-stayed bridge is used as a numerical substructure. For the control of the loading, a hydraulic jack manually operated based on the command indicated by the test control PC is used. Since the test procedure can involve inaccuracies in imposing the designated displacement, a detailed experimental error evaluation is conducted, showing that the ratio of the error in the response is acceptably small. Reliability of the seismic performance assessment of the retrofitted cable-stayed bridge to check the structural response satisfying required allowable limit states is discussed.

Keywords: Seismic retrofit, long-span bridge, pseudo-dynamic test, seismic response modification device

1. INTRODUCTION

Installation of additional energy dissipation devices has become one of the viable and effective options for seismic retrofit of long-span cable-stayed bridges to ensure required seismic performance, in addition to the conventional retrofit strategies. Energy dissipation devices for this purpose are required to have large stroke capacity and ability to generate high damping forces, 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 attempt to employ new type of devices such as the laminated high damping rubber damper to a long-span bridge, seismic performance of the system is usually assessed by means of numerical seismic response analysis incorporating a numerical model of the new device to be implemented. However, check of the reliability of the device subjected to the seismic action as well as the validation of the numerical simulation of the seismic response can be problematic due to the scale of the test device and dynamic interaction between the device and the long-span cable-stayed bridge.

In this paper, applicability of the hybrid simulation technique as a measure to evaluate seismic performance of a cable-stayed bridge retrofitted with laminated high damping rubber dampers is investigated. In the hybrid simulation test, the experimental substructure is a laminated high damping rubber damper specimen of 1/4 scale to the prototype device, consisting of four laminated rubber assemblies, connecting and supporting plates, and a dynamic MDOF model of the cable-stayed bridge is used as a numerical substructure. For the control of the loading of the device in the process of the hybrid simulation, a hydraulic jack manually operated based on the command indicated by the test control PC is used.

Since the test procedure can involve inaccuracies in imposing the designated displacement, a detailed experimental error evaluation is indispensable to show the reliability of the hybrid simulation result. The error of the simulation is evaluated in terms of the imbalance in the equilibrium of the system, i.e. discrepancy of the value of the left hand side of the equation of motion for the MDOF system from the seismic load term used in the numerical time integration scheme. Based on the test result and the error evaluation, reliability of the seismic performance assessment of the retrofitted cable-stayed bridge to check the structural response satisfying required allowable limit states is discussed.

2. SEISMIC RETROFITTING OF LONG-SPAN CABLE-STAYED BRIDGE

2.1. Cable-Stayed Bridge Retrofitted

The structure to be used in the present study analyzed is Higashi Kobe Bridge, located in Kobe, Japan, for which structural upgrading project for seismic retrofitting using the proposed laminated rubber damper was conducted (Nagasawa et al. 2010). Higashi Kobe Bridge is a 3-span continuous girder cable-stayed bridge, with dimensions shown in Figure 2.1 and Table 1. The main girder was allowed longitudinal displacement with the use of the “all-free type” design to achieve a reduced seismic demand to the pylon, resulting in the longitudinal fundamental period of 4.3 sec. The oil-type vane dampers were installed at the ends of the girder so as to obtain 2% damping ratio for the longitudinal vibration of the girder, which later found to be insufficient for large magnitude inter-plate earthquake ground motions.

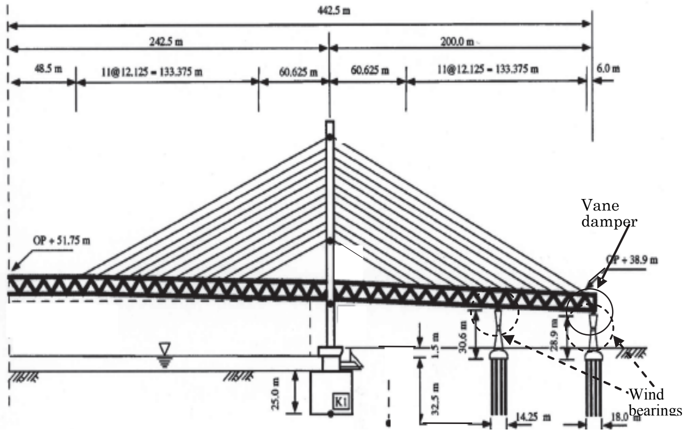


Figure 2.1. Elevation view of Higashi Kobe Bridge

Table 2.1. Dimensions of Higashi Kobe Bridge

Length	200+485+200=885m
Width	13.5m (2 decks)
Height of Pylon	146.5m
Main Girder	Warren truss (Height 9m)
Cables	Harp type (12 parallel)
Weight	Main girder 14,100 tf Pylon 7,900 tf Cables 1,300 tf Abutment 1,700 tf Others 2,400 tf

2.2. Seismic Retrofitting with Laminated Rubber Dampers

The layout of the laminated rubber damper used for the large cable stayed bridge retrofit is shown in Figure 2.2. Four laminated high damping rubber (HDR-S) assemblies are placed inside a casing rigidly connected to the pylon. As the center plate connected to the main bridge girder with cables moves in the horizontal longitudinal direction, the laminated rubber assemblies are subjected to shear deformation while the damping force is generated by the shear stress in the laminated rubber. Cable connection is employed to avoid torsional and flexural stresses that can be induced, were the dampers directly connected to the girder. The laminated high-damping rubber assembly used for the damper is square-shaped, with dimensions of 1150 x 1150 mm and rubber layer thickness of 25 mm (per layer) and 200mm (total).

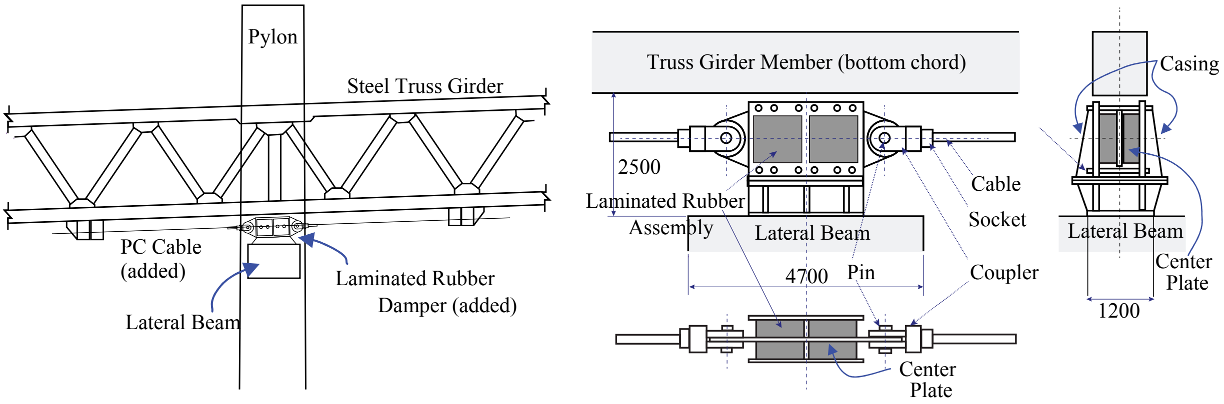


Figure 2.2. Retrofit of cable-stayed bridge with laminated rubber dampers

2.3. Performance Requirement for Laminated Rubber Damper

The dimensions and specifications of the laminated rubber components were determined so that the longitudinal girder displacement is limited within the allowable limit of 0.9m neglecting the damping provided by the existing vane dampers, as well as accounting for the allowable strain of the pylon and piers. As the result of numerical dynamic analysis of Higashi Kobe Bridge model for the seismic performance assessment, the seismic performance requirement for Level-2 earthquakes is shown to be satisfied by specifying the allowable strain of 300% in the laminated rubber and verifying that laminated rubber assemblies should not fail and maintain the energy dissipation capability at 325% shear strain, taking the effects of rubber material uncertainty into account (Nagasawa et al. 2010). A verification test program for this type of energy dissipation device was conducted, with successful test results that show the performance of laminated rubber damper with four high-damping rubber assemblies satisfy the requirement (Igarashi et al. 2009a).

2.4. Objective of Hybrid Simulation for Laminated Rubber Damper

As in this typical application of a new type of energy dissipation device, the performance of the cable-stayed bridge can be shown by numerical simulation, provided that the numerical model of the force-displacement response is accurate and reliable. However, a number of disturbing factors associated with the device response exists, including the complicated nonlinear behavior that does not allow accurate formulation, uncertainty in the properties of the device material, degradation, overstrength or time dependency, and possible loss of integrity of the device mechanism during actual and realistic loading condition. These factors affect the verification procedure in many cases. Use of the hybrid simulation or pseudo-dynamic testing technique is an acceptable strategy to provide a dependable verification process in those situations.

In this study, hybrid simulation of the laminated rubber damper is conducted to show that the performance requirement for the cable-stayed bridge with respect to the maximum girder displacement within the allowable value of 0.9m, and the bending moment at the base of the pylon leg within the allowable value of 1,235,000 (kN m) is satisfied based on the loading test of a test specimen of the energy dissipation device. Applicability of the hybrid simulation technique to practical design assessment issues can be demonstrated by investigating this process as a representative case that verification of a new device is needed.

3. TEST DESCRIPTION

The test specimen representing the laminated rubber bearing is prepared as a 1/4 scaled model of the actual device. A series of hybrid simulation using the test specimen were conducted. In this section, the test device, loading system and hybrid simulation and particular feature of the test method used in this study is described.

3.1. Test Device Specimen

The laminated rubber damper test specimen is shown in Figure 3.1 and Table 3.1. Four laminated rubber assemblies are of 1.2 N/mm^2 class shear modulus of the HDR-S rubber and placed within two steel panels rigidly connected to the strong floor. The load is applied to the center plate connected to the four laminated rubber assemblies using a hydraulic jack in the horizontal direction. Table 3.1 also shows the comparison with the prototype device. The scale factor of 1/4 was determined based on the maximum loading capacity of the hydraulic jack as 2000kN.

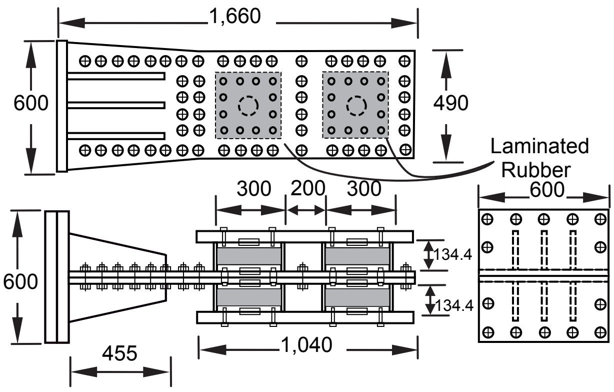


Figure 3.1. Dimensions of Test Device Specimen

Table 3.1. Prototype and Scaled Model of Device

			Prototype	1/4 Model
Shear Modulus *G*		N/mm^2	1.2	1.2
Unit dim.	Dimensions	mm	1,150×1,150	300×300
	Area	m^2	1.32	0.09
	Layer thickness	mm	25	7
	# of layers		8	8
	Total thickness	mm	200	56
	S_1		11.5	10.7
	S_2		5.75	5.36
Chr. val.	Max. strain	%	325	325
	Yield displ.	mm	13.6	3.8
	Yield load	kN	1,034	70
	Max. displ.	mm	650	182
	Max. load	kN	5,680	387
	Init.stiffness	kN/m	75,867	18,439
	Post-yield st.	kN/m	7,179	1,745

3.2. Test Setup

The hydraulic jack used in the test is of static loading, shown in Fig. 3.2, with the maximum load capacity of 5000kN (compression) / 2390kN (tension), and the maximum displacements of +/- 400mm. The hydraulic jack is manually controlled with the switches corresponding to the operations of charging, discharging or holding the oil pressure.

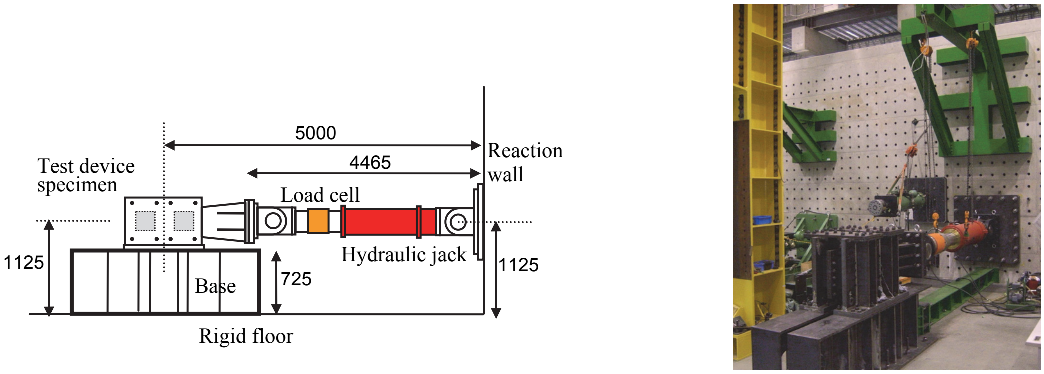
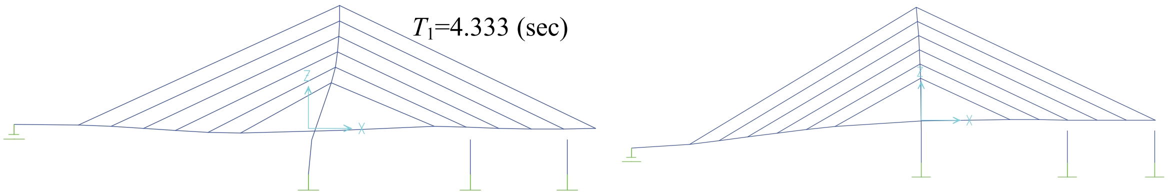


Figure 3.2. Test Setup

3.3. Hybrid Simulation

3.3.1. Numerical model of cable-stayed bridge

The 1st and the 2nd modes of the cable-stayed bridge calculated with a 66-DOF finite element numerical model are shown in Figure 3.3. The first and second modes correspond to longitudinal and lateral motions 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.



(a) 1st Mode **(b)** 2nd Mode

Figure 3.3. Natural Modes of the Cable-Stayed Bridge Model

For the hybrid simulation, the bridge including the laminated rubber damper connected to the tower and the girder is reduced to a 3-degree-of-freedom model to execute fast calculation of the response for fast loading test of the damper, as shown in Figure 3.4. The masses 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 represent the flexural stiffness of the tower and the axial stiffness of cables. 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.

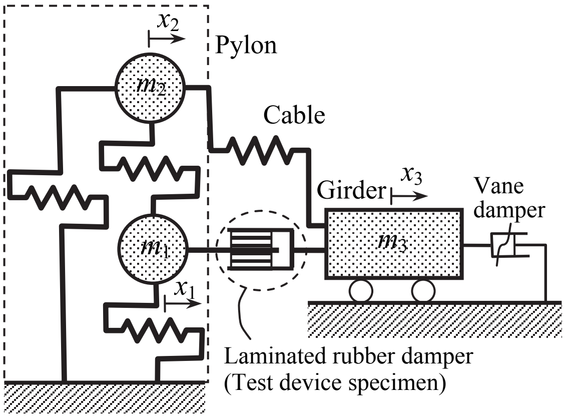


Figure 3.4. Reduced 3-DOF Model of the Bridge

Table 3.2. Characteristic values of the reduced 3-DOF Model

	Natural Period	Damping Ratio
1st Mode	4.2 (sec)	0.050
2nd Mode	0.90 (sec)	0.031
3rd Mode	0.25 (sec)	0.201

3.3.2. Special consideration for numerical model

Step-by-step time integration of the equation of motion expressed by Eq.(1) is performed in the hybrid simulation.

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)+\mathbf{f}_d(t)=-\mathbf{M}\mathbf{1}\ddot{z}(t) \tag{3.1}$$

where **M**, **C**, **K** are the mass, damping and elastic stiffness matrices, respectively, $\mathbf{x}(t)$ is the displacement vector, $\mathbf{f}_d(t)$ is the restoring force vector obtained by the test measurement, $\ddot{z}(t)$ is input ground acceleration. The damping matrix **C** is specified based on the typical modal damping ratio of steel structures as 0.03, the equivalent damping of the vane damper. In addition, in order to suppress the appearance of spurious higher mode response often induced by the experimental error, the modal damping ratio for the 3rd mode is intentionally increased to h_3 =0.2. The characteristics values are summarized in Table 3.2

3.3.3. Algorithm for manually operated hybrid simulation

The Operator Splitting method is adopted as the step-by-step time integration scheme. Hybrid simulation is performed in the manner such that at each time step, the displacements of the nodes that are connected to the experimental substructure are imposed on the test specimen using the hydraulic jack, and the load of the test specimen is measured to be used in the time integration. In this process, the similitude between the prototype structure and the scaled test specimen are considered in appropriate scaling of the displacements to be imposed and of the measured restoring force provided to the time integration algorithm (Igarashi et al. 2009b).

Although it is quite common to operate the loading jack to impose the displacements on the test specimen by a computer-based on-line control, the manual operation of the hydraulic jack was adopted for the hybrid simulation in this study, because of lack of a servo control mechanism and operation via external signals. The test control PC computes the next target displacement and shows the value, as well as the associated manual operation on the pump control (charge or discharge of the oil pressure) to achieve the value on the display screen. The human operator manually operates the hydraulic controller as directed by the test control program to obtain the target displacement within the error tolerance. The test control PC continuously monitors the measured displacement, and when the monitored displacement becomes sufficiently close to the target, the measured values are recorded and the time integration at the next step is computed. This process is repeated until the end of the simulation.

4. HYBRID SIMULATION FOR ACCURACY EVALUATION

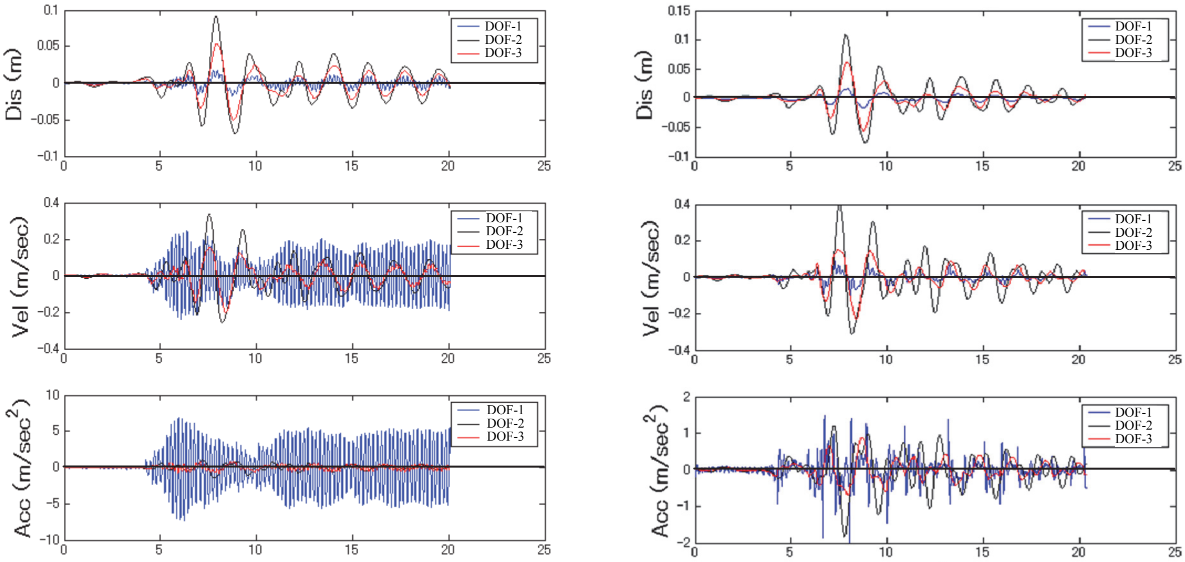
It is anticipated that control errors in the displacement imposed on the test device can possibly be larger than ordinary cases, since a manual operation by the human operator is involved in the control of the hydraulic jack in this study. Therefore, the need of evaluation of the difference in the simulation results introduced by the experimental error is of particular interest greater than usual cases. For this purpose, a series of tests were performed using a scaled input ground motion based on an accelerogram recorded during 1995 Hyogoken Nanbu earthquake at the site of Higashi Kobe bridge. The input ground motion is a spectrum-compatible accelerogram II-III-1 for Level-2 earthquake specified in the bridge design code in Japan (Japan Road Association, 2002) as one of the standard accelerograms.

In order to evaluate the accuracy of the hybrid simulation result, the displacement, velocity and relative acceleration vectors obtained in the hybrid simulation are substituted into the equation of motion Eq.(3.1), and the right hand side and the left hand side of the equation are compared. Accumulation of the error should be revealed as the difference between the right hand side and left hand side of the equation.

The accuracy is evaluated in two cases of hybrid simulation; Case-1: The modal damping for all three modes are uniformly set to 0.03, and Case-2: The modal damping for all the lower two modes are set to 0.03, and that of the highest mode is set to 0.2. Damping due to the vane damper which is primarily effective in the first mode is added in both cases. The two cases are summarized in Table 4.1.

Table 4.1. Cases of accuracy evaluation

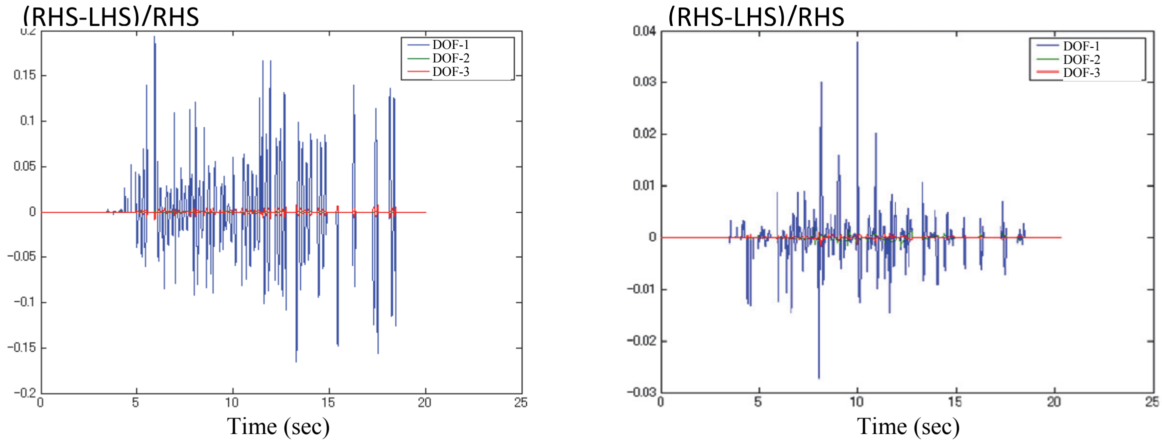
	Natural Period	Modal Damping Ratio	
		Case-1	Case-2
1st Mode	4.2 (sec)	0.050	0.050
2nd Mode	0.90 (sec)	0.031	0.031
3rd Mode	0.25 (sec)	0.031	0.201



(a) Case-1 (b) Case-2

Figure 4.1. Test Results: Response Time Hisotry

The results of the hybrid simulation are shown in Fig. 4.1. The values of the plots are in the scale of the prototype bridge considering similitude. In Case-1, effect of spurious higher mode response with the period of 0.3 sec can be observed in displacement, velocity and acceleration plots. The spurious response is particularly large in DOF-1, which corresponds to the response of the pylon at the location of damper installation. On the other hand, the spurious higher mode response of DOF-1is significantly reduced owing to the increased damping for the 3rd mode. It should also be noted that the response of DOF-2 and DOF-3 are almost unaffected by the increase of the damping in the highest mode, for which the natural frequency is regarded as not within the spectral range of interest. For the quantitative evaluation of these observations, plots of relative error in the difference between the left hand side and right hand side of the equation of motion, that can be regarded as an imbalance, is calculated and shown in Fig. 4.2.



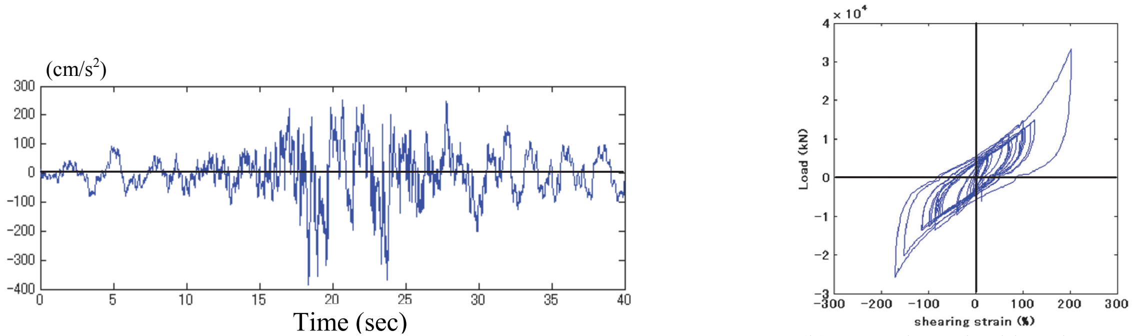
(a) Case-1 (b) Case-2

Figure 4.1. Test Results: Accuracy Evaluation by Inbalance in Equation of Motion

The imbalance between the right and left hand sides for Case-2 is evaluated to be within 4% in terms of the maximum values, and almost within 1% except for a limited instance of the time. In contrast, the imbalance can be as large as 20% maximum values in Case-1. This quantity can be a reasonable indicative parameter to evaluate the accuracy of the hybrid simulation, even using the control of the hydraulic jack with manual operation.

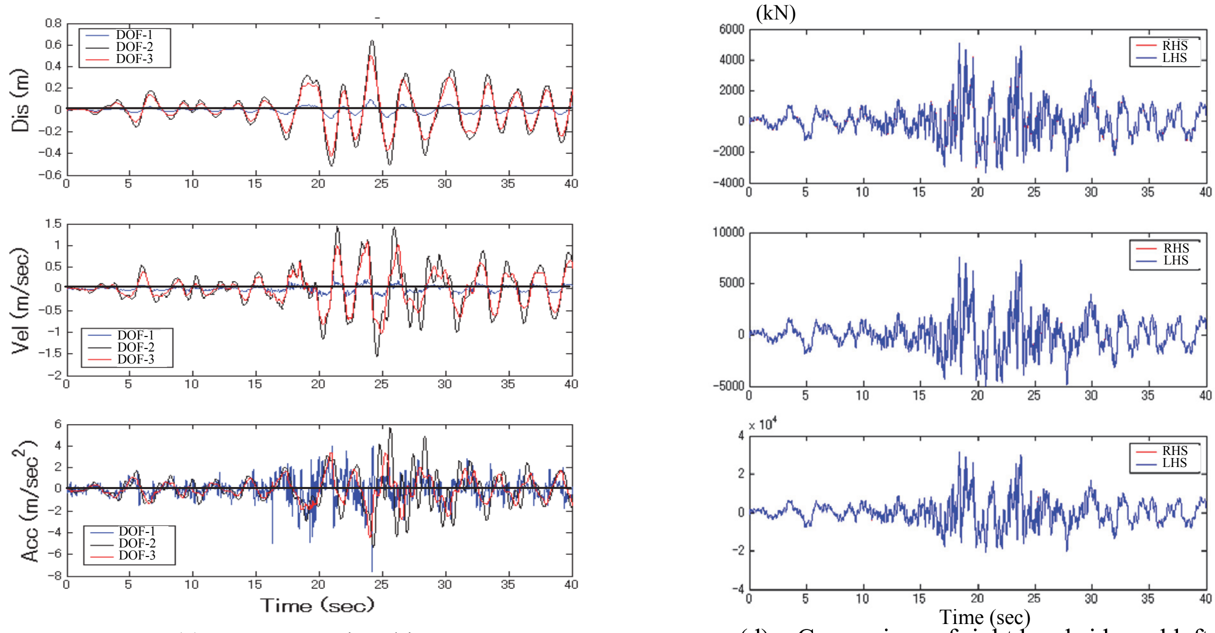
5. HYBRID SIMULATION FOR SEISMIC PERFORMANCE ASSESSMENT

A series of hybrid simulation using an accelerogram created for the performance assessment of Higashi Kobe bridge, considering the earthquake source and site condition were conducted. Based on the result of the accuracy evaluation, damping of Case-2 was employed in the hybrid simulation. The input accelerogram for performance assessment is the most critical Level-2 ground motion at the site for Higashi Kobe Bridge. The accelerogram of the input, and the test results are shown in Fig. 5.1. The evaluation of the right hand side and left hand side of the equation of motion is shown in Fig. 5.1 (d), indicating a good agreement each other in this case.



(a) Input accelerogram

(b) Laminated rubber damper hysteretic response



(c) Response time history

(d) Comparison of right hand side and left hand side of equation of motion

Figure 5.1. Hybrid simulation using input accelerogram for seismic performance assessment

From the test result, the maximum girder displacement is found to be 50.7cm, which is within the target allowable girder displacements in the seismic retrofit, although the effect of vane damper is included. Furthermore, the maximum moment at the pylon leg base is estimated by using this test result. A pushover analysis of the finite element model apply longitudinal loads to the girder is conducted to find that the maximum moment is 1,080,000 kN m. This value is less than the allowable limit value of 1,235,000 kN m.

6. CONCLUSION

In this paper, applicability of the hybrid simulation technique as a measure to evaluate seismic performance of a cable-stayed bridge retrofitted with laminated high damping rubber dampers is investigated. In the hybrid simulation test, the experimental substructure is a laminated high damping rubber damper specimen of 1/4 scale to the prototype device, consisting of four laminated rubber assemblies, connecting and supporting plates, and a dynamic MDOF model of the cable-stayed bridge is used as a numerical substructure. For the control of the loading of the device in the process of the hybrid simulation, a hydraulic jack manually operated based on the command indicated by the test control PC is used. Since the test procedure can involve inaccuracies in imposing the designated displacement, the accuracy of the simulation is evaluated by comparing the right hand side and the left hand side of the equation of motion after substituting the obtained response value.

It is found that if an increased modal damping is used for the highest mode, the amount of error and the effect of spurious higher mode response becomes significantly small. It is demonstrated that using this choice of system damping, hybrid simulation to assess the seismic performance of a long-span cable-stayed bridge can be successfully conducted with acceptable accuracy.

AKCNOWLEDGEMENT
The authors took advantage of using the test equipment setup and extra test specimen prepared for the joint research of Kyoto University and Hanshin Expressway Corporation on the verification test of the laminated rubber bearings in conducting the research presented in this paper. The authors also would like to express their gratitude for the assistance of Mr. Kazuma Inoue.

REFERENCES

Iemura, H., Igarashi, A. and Toyooka, A. (2008). Development of an innovative seismic damper for large-scale bridges and sub-structured hybrid earthquake loading tests, *4th Int. Conf. on Bridge Maintenance, Safety and Management (IABMAS08)*, **4**, 515-(8 pp.).

Igarashi, A., Inoue, K., Taya, F., Iemura, H. Yoshida,M., Himeno, T. and Nagasawa, M. (2009). Fundamental performance evaluation of energy dissipation device consisting of multiple laminated rubber assemblies by means of cyclic loading tests (in Japanese), *Journal of Japan Society of Civil Engineers*, **Ser. A1**, **65:1**, 450-455.

Igarashi, A., Sanchez-Flores, F., Iemura, H., Fujii, K., Toyooka, A. (2009). Real-time hybrid testing of laminated rubber dampers for seismic retrofit of bridges, *3rd Intionational Conference on Advances in Experimental Structural Engineering (3AESE)*, 10pp.

Nagasawa, M., Sumi, K., Tasaki, K. and Iemura, H. (2010). Seismic retrofit of all-free type cable-stayed Higashi-Kobe Bridge with new energy dissipation devices, *5th Int. Conf. on Structural Control and Monitoring (5WCSCM)*, Paper No.110.