



HYBRID TEST ON BASE-ISOLATED STRUCTURES USING COMBINED DISPLACEMENT-FORCE CONTROL

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SUMMARY

The paper proposes online test methods using displacement-force mixed-control. Two types of mixed-control are devised. In one control, named “combined-control,” one jack is loaded by displacement-control, and the other jack is loaded by force-control; in the other control, named “switching-control,” one jack is loaded sometimes by displacement-control and other times by force-control. The loading and control system to realize the mixed-control is devised, and their effectiveness is demonstrated by a series of online tests applied to a base-isolated structure. Accurate control for both the displacement and force is achieved in the combined-control, and switching between displacement-control and force-control is realized successfully in the switching-control.

INTRODUCTION

The online computer-controlled test (also referred to as the pseudo-dynamic test and simply called the online test in this paper) has a history of nearly thirty years, and is becoming a standard test procedure in earthquake engineering research [1-4]. The online test is in essence a test with displacement-control. Displacement-control, however, is no longer effective when the test structure is too stiff to accurately control the loading actuator’s displacement. There are cases when we like to apply online tests to stiff structures. A practical example is given below. Let us suppose an online test applied to a base-isolated building using the substructuring techniques in which only isolation devices, say, rubber bearings are tested. It is well known that the horizontal restoring forces of rubber bearings are affected strongly by the axial forces exerted on the bearings due to the combination of gravity, overturning moment and vertical vibration. This means that we shall accurately impose axial forces onto the tested rubber bearings to obtain accurate horizontal restoring forces. Displacement-control for the vertical direction (to impose accurate vertical forces) is not feasible because of very high stiffness in this direction, while conventional displacement-control is still practicable to apply flexible horizontal deformations. In such a case, a combined control by displacement (for the flexible horizontal direction) and force (for the stiff vertical direction) is appealing. Another example is an online test to simulate the responses of a base-isolated

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structure subjected to vertical ground motion. The rubber bearings are very stiff as long as they sustain compression but become all of a sudden very flexible once they sustain tension. During the responses when the rubber bearings sustain compression, force-control is more practical, whereas displacement-control is a natural choice once they sustain tension.

In light of these situations in which force-control is more feasible in the online test, the paper introduces online tests in which mixed-control of displacement and force are employed. Two types of mixed-control are considered in this paper. One, named displacement-force combined-control, is a control in which one jack is operated in displacement-control, while the other operated in force control. The other, named displacement-force switching-control, is a control in which one jack is controlled by displacement sometimes and by force otherwise.

LOADING SYSTEM

Hardware Development

The loading system shown in Fig. 1 was developed for the mixed-control online test presented in the study. Primary hardware devices include: (1) two quasi-static loading jacks; (2) two hydraulic pump systems activated by an inverter motor each of which supplies oil to one jack; (3) two load cells, each of which measures the reactionary force of one jack; (4) two digital displacement transducers, each of which measures the displacement of one jack; (5) two pump controllers that control the frequency of the inverter motor to adjust the jack's ram speed; (6) a switch box and data logger that collects strain gauge, LVDT, and other data; (7) a PC that controls the controllers, named "PC for Control", and (8) a PC that supervises "PC for Control" and stores the data collected by the data logger, named "PC for Operation."

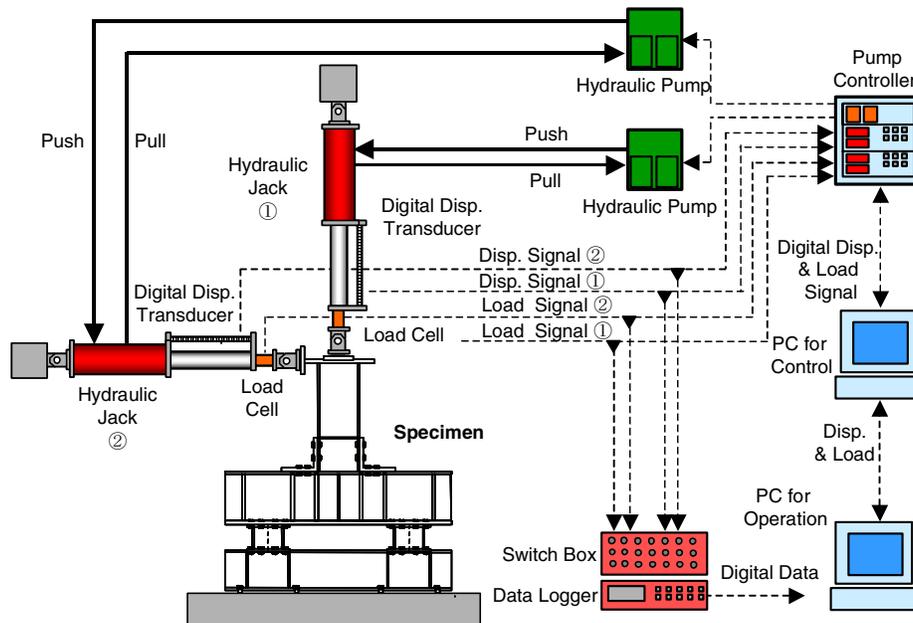


Fig. 1 Outline of online test system developed

Notable features of the system are as follows. Unlike conventional LVDTs in which the resolution decreases for a larger stroke, this digital displacement transducer maintains a resolution of 0.01 mm regardless of the total stroke. Unlike conventional hydraulic pumps, an inverter motor that can adjust its frequency has been used, thereby making it possible to control the rate of oil flow and accordingly the jack's ram speed. For loading, the pump unit selects the chamber into which oil is to flow ("push" or

“pull”). The chamber is selected using a solenoid valve, and the frequency of the motor is set in proportion to a voltage signal. Unloading is accomplished by releasing oil through a high-speed on-off valve. The frequency of this valve, i.e., the rate of oil release, is set also in proportion to a voltage signal to adjust the jack’s ram speed during unloading. The jack’s ram speed that can be adjusted in the system ranges from 0.02 to 2 mm/sec. The controller selects the direction of jack motion (“push” or “pull”), the frequency of the inverter motor during loading, the frequency of the valve during unloading, and changes between the loading and unloading modes. The controller can adopt either force or displacement control. The controller keeps monitoring the current status (both displacement and force) after every 10 msec and adjusts signals for smooth operation.

Computation and Control

“PC for Control” is connected to the two jack controllers, sending the target displacements or forces assigned for the two jacks and the time set for loading, both in digital forms, to the controllers. During loading, it receives the displacement and force values from the two controllers continuously and adjusts the loading by monitoring deviation of the measured signals from the commanded signals. “PC for Operation” has two major functions: to trigger a data logger for data collection and store the data, and to create and send the displacement or force signals to “PC for Control”. When the system is used for the online test, the associated equations of motion are solved in this PC. As soon as one step of loading is completed, the controllers send a set of displacement and force values to “PC for Control”, and “PC for Control” passes the values to “PC for Operation”. Then “PC for Operation” sends a trigger signal to the data logger, asking for data collection. Upon receiving this signal, the data logger starts collecting and sending the data to “PC for Operation”. Note that during this process the jacks hold the structure at rest. “PC for Operation” creates and sends displacement or force signals to “PC for Control”. More details on the developed system are found elsewhere [5, 6].

Characteristics for Mixed-Control

The following three characteristics are incorporated into the system to achieve realistic implementation of mixed-control. First is the feedback mechanism of the controller shown above. In the displacement-force combined-control, two jacks are operated simultaneously, one with displacement-control and the other with force-control. Movement of one jack is interfered with movement of the other jack. The feedback mechanism of the controller, with the feedback frequency of 100 Hz, accomplishes tuned, proportional loading of the two jacks. Second is the use of quasi-static jacks. The maximum ram speed is at most 2 mm/sec, which avoids uncontrollable flow of oil and eventual jack’s movement that may endanger the test operation. This slowness is particularly beneficial when the control mode is switched from displacement to force or from displacement to force in the displacement-force switching-control. Third is the encapsulated framework adopted in the test system, which makes the programmer to be able focus on the mixed-control algorithm without knowing all the hardware details. An ActiveX control [7], which is programmed in the C++ language by experts in hydraulics and control, is installed on “PC for Operation.” It provides all the programming interfaces for hardware control. The programmer, who is not necessarily seasoned with hardware control, only needs to work on “PC for Operation.”

STRUCTURAL MODEL, TEST SETUP, AND TEST SPECIMEN

Base-Isolated Structure

The proposed loading system was used to simulate earthquake responses of a base-isolated structure subjected to horizontal and vertical ground motions. The structure considered is shown in Fig. 2(a), which is an eight stories and two spans steel moment planar frame isolated by high damping rubber bearing (HDRB). The substructuring technique was employed, and the superstructure (the steel moment frame) and base-isolation layer (consisting of two HDRBs) were assigned as the computed part and the tested part, respectively. As shown in Fig. 2(b), the superstructure was modeled as a linear spring-mass system,

with one mass per floor and one horizontal spring and one vertical spring per story. The equations of motion were formulated for an eighteen DOFs system, with one horizontal and one vertical DOF added for the base-isolation layer. The natural periods of the base-isolated structure are listed in Table 1.

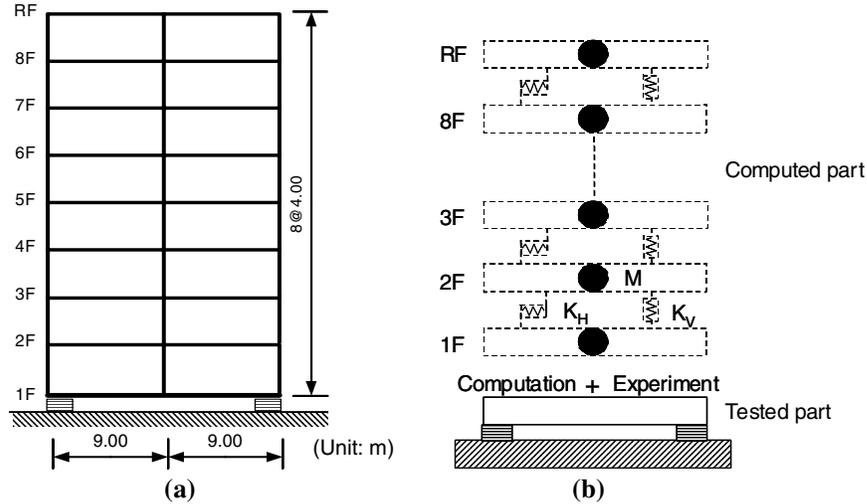


Fig. 2 Base-isolated structure: (a) basic dimensions; (b) division into substructures

Table 1 Natural period of base-isolated structure

	Horizontal		Vertical	
	Base-fixed	Base-isolated	Superstructure	Entire structure
Period (s)	1.263	3.760	0.24	0.25

Test Setup

The test setup, shown in Fig. 3(a), includes the loading frame, two jacks (one for horizontal loading and the other for vertical loading), and the test specimen. The test specimen featured two identical HDRBs. Two jacks were attached to the inverted T-shaped loading frame, which in turn was clamped to the HDRBs. The two rubber bearings were placed 1.0 m apart in the center-to-center length, and the jacks were attached at a height of 1.5 m, measured from the bottom of the HDRBs to the top of the T-shaped loading frame [Fig.3(b)]. Fig. 3(b) also shows the measurement details. Because of large stiffness of the T-shaped loading frame and the rubber bearings when subjected to compression, the jack's horizontal and vertical displacements were the same as the horizontal and vertical displacements of the test specimen.

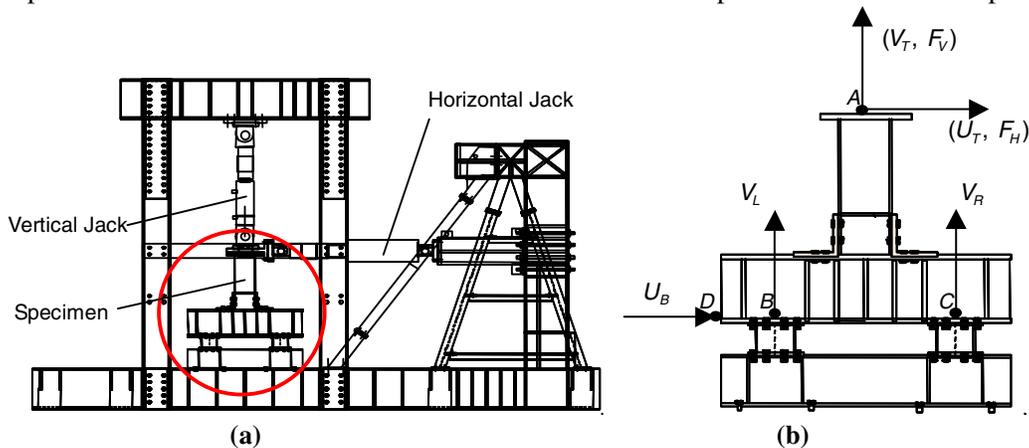


Fig. 3 Test setup: (a) test specimen and loading frame; (b) details in measurement

In reference to the vibration of the base-isolated structure, three independent loads, i.e., the horizontal load, vertical load, and overturning moment, should be controlled for the test specimen. Because the test system of Fig. 3(a) was featured only with two jacks, it was assumed that the overturning moment applied to the base-isolation layer was always proportional to the horizontal force to the layer. Then, the adopted loading system, in which both the horizontal force and overturning moment were applied by the horizontal jack through the inverted T-shaped loading frame, was justified. The HDRBs of the test specimen had the dimensions with a diameter of 200 mm and a total rubber thickness of 85 mm. From comparison in the cross-sectional area, the total rubber thickness, the shape factors, rubber's shear modulus between the prototype HDRBs and the test ed HDRBs, the scale-ratios of 1 to 4 and 1 to 20 were adopted for the horizontal displacement and horizontal force, respectively.

DISPLACEMENT-FORCE COMBINED-CONTROL

Algorithm for Displacement-Force Combined-Control

Preliminary static tests were carried out to examine the horizontal restoring force characteristics of the In the proposed control, displacement-control and force-control were adopted for loading of the horizontal and vertical jacks, respectively. The integration method using the operator-splitting (OS) scheme [8, 9] was employed for displacement-control. Note that the online test using the OS scheme ensures unconditional stability if the initial stiffness is taken as the linear stiffness and the nonlinearity is of softening type [9]. The basic formulations are described as follows:

$$Ma_{n+1} + Cv_{n+1} + K^I d_{n+1} + K_{n+1}^E \tilde{d}_{n+1} = P_{n+1} \quad (1)$$

$$\tilde{d}_{n+1} = d_n + \Delta t v_n + (\Delta t^2 / 4) a_n \quad (2)$$

$$d_{n+1} = \tilde{d}_{n+1} + (\Delta t^2 / 4) a_{n+1} \quad (3)$$

$$v_{n+1} = v_n + (\Delta t / 2)(a_n + a_{n+1}) \quad (4)$$

In which, K^I and K_{n+1}^E are the linear and nonlinear stiffness matrices, M and C are the mass and viscous damping matrices, \tilde{d} and d are the predictor and corrector displacement vectors, v and a are the velocity and acceleration vectors, and Δt the integration time interval. The procedure of implementation is as follows:

- (1) Set up the equations of motion as shown in Equation (1).
- (2) Set the initial stiffness matrix of the structure at K^I based on the preliminary static test.
- (3) Apply the predictor displacement \tilde{d}_{n+1} to the structure and measure the corresponding reactional force f_{n+1} [see Fig. 4(a)].
- (4) Calculate $f_{n+1} - K^I \tilde{d}_{n+1}$, substitute it into the term $K_{n+1}^E \tilde{d}_{n+1}$, and calculate the corrector displacement d_{n+1} .

The algorithm when applied to force-control is also based on the OS scheme. In implementation of this algorithm, Steps (1) and (2) are identical with the procedure above, but in Step (3), the predictor force \tilde{f}_{n+1} , which is taken to equal $K^I \tilde{d}_{n+1}$ is applied to the structure [see Fig. 4(b)]. Here, K^I is the elastic stiffness, and the structure is assumed to behave only elastically. Then, the term $f_{n+1} - K^I \tilde{d}_{n+1}$ in Step (4) becomes zero, and the procedure is made identical to the unconditionally stable implicit Newmark method.

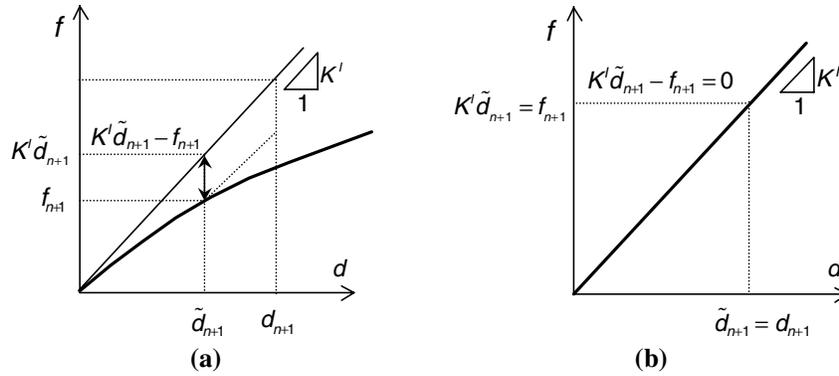


Fig. 4 Outline of displacement-force combined-control algorithm: (a) inelastic behavior for horizontal response; (b) elastic behavior for vertical response

Online Test Using Displacement-Force Combined-Control

The responses of the base-isolated structure shown in Fig. 2 were simulated. It was assumed that both the superstructure and base-isolation layer would respond linearly in the vertical motion. Because of this assumption, the nine degrees in the horizontal direction and the other nine degrees in the vertical direction are uncoupled in the equations of motion, but interaction still exist between the horizontal and vertical responses in that the effect of the vertical forces on the horizontal restoring force of the test specimen was automatically taken into account in the physical test. A ground motion recorded at the Japan Meteorological Agency (JMA) in the 1995 Hyogoken-Nanbu earthquake was chosen as the input ground motion [10]. The fault-normal and vertical components were adopted as the horizontal and vertical excitations, respectively. The vertical ground motion did not cause tension in the bearings.

For the purpose of comparison, two tests (Tests A and B) were carried out. In Test A, the response when subjected to the horizontal ground motion only was simulated. In Test B, the response when subjected to the horizontal and vertical ground motions simultaneously was simulated. In both tests, vertical load corresponding to gravity (250 kN) was imposed at the beginning of the test. The force-displacement relationships and displacement time histories are shown in Fig. 5(a) and (b), respectively. In the figures, the thin and thick solid lines represent Tests A and B. Behavior of the test specimen for Test B, in which both the horizontal and vertical ground motions were applied simultaneously, is significantly more complicated than the behavior for Test A. In Fig. 5(a), the horizontal stiffness of the test specimen fluctuates in tune with the variation of the axial force. As a result, the displacement time history of the base-isolation layer is somewhat different, with the difference of the maximum displacement of about 15%, between Tests A and B.

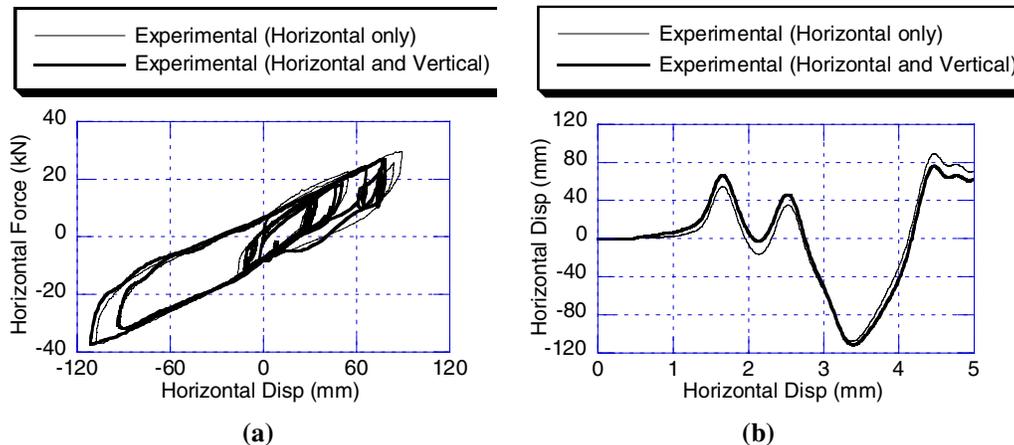


Fig. 5 Responses obtained by online tests: (a) hysteresis curves; (b) displacement time histories

FORCE-DISPLACEMENT SWITCHING-CONTROL

Preliminary Static Test for Displacement-Force Switching-Control

Online tests using displacement-force switching-control were carried out for the simulation of responses of the base-isolated structure [Fig. 2(a)] when subjected to vertical ground motion. Preliminary static tests were conducted to examine the test specimen's behavior for vertical loads. The loading program adopted was as follows: A compressive vertical load was applied monotonically to a force of 500 kN, then it was unloaded to zero. Next, tensile vertical load was applied to a vertical elongation of 25 mm (corresponding to about a 30% tensile strain in the rubber), and unloaded again. This loading was repeated twice. The vertical forced-displacement relationships obtained is plotted in Fig. 6. As shown in this figure, the vertical stiffness differs notably between compression and tension, and the strength in tension is very small, exhibiting a small yield force and a large plastic deformation afterward.

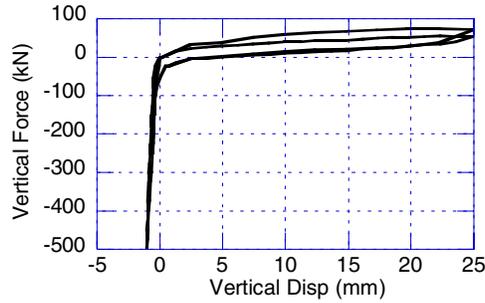


Fig. 6 Vertical force-displacement relationship

Algorithm of Displacement-Force Switching-Control

In the displacement-force switching-control devised in this study, one jack was force-controlled when the test specimen (HDRBs) sustained compression, and displacement-controlled when it sustained tension. Similar to the displacement-force combined-control, the OS scheme was used for direct integration. During the force-control, the force equal to the product of the predicted displacement and the assumed vertical stiffness was applied to the test specimen, while the conventional displacement-control was employed. The control mode was switched when the sign of the force changed from compression to tension or from tension to compression. The integration algorithm for computation is as follows.

- (1) Set the initial stiffness based on the preliminary compression test, and set control mode at force-control.
- (2) Apply a compressive force corresponding to gravity to the test specimen and measure the corresponding displacement, which is set to be the initial displacement.
- (3) Compute the predictor displacement \tilde{d}_{n+1} .
- (4) Compute the predictor force \tilde{f}_{n+1} by $K^I \tilde{d}_{n+1}$.
- (5a) If \tilde{f}_{n+1} is negative, the test specimen is taken to sustain compression, and force-control is adopted.
- (5b) If \tilde{f}_{n+1} is positive, the test specimen is taken to sustain tension, and displacement-control is adopted.
- (6a) In force-control, apply the computed load to the structure, substitute zero into the term $K_{n+1}^E \tilde{d}_{n+1}$, and compute the corrector displacement d_{n+1} .
- (6b) In displacement-control, apply the predicted displacement, measure the reactional force f_{n+1} , compute $f_{n+1} - K^I \tilde{d}_{n+1}$, substitute it into the term $K_{n+1}^E \tilde{d}_{n+1}$, and compute the corrector displacement d_{n+1} .

Figure 7(a) shows the details of switching the control mode from force to displacement. In Step n , the test specimen is lead to Point A by force-control, sustaining compression. The predictor-displacement computed for Step $n+1$ is positive. Then control mode is switched from force to displacement, and the

test specimen is lead to Point B. The corresponding force is measured and used for computation for the following step. Figure 7(b) shows the details of switching the control mode from displacement to force. In Step n , the test specimen is lead to Point A by displacement-control. The predictor displacement computed for Step $n+1$ is negative, and the control mode is switched for force-control. According to the algorithm, the force equal to $K'\tilde{d}_{n+1}$ is supposed to be applied. As shown in Fig. 7(b), the force can be very large, because the displacement at Point A is not necessarily zero. This force may create a large imbalanced energy in the computation. To avoid this, varying time integration was adopted for the steps when the control-mode is switched from displacement to force as shown [Fig. 7(c)].

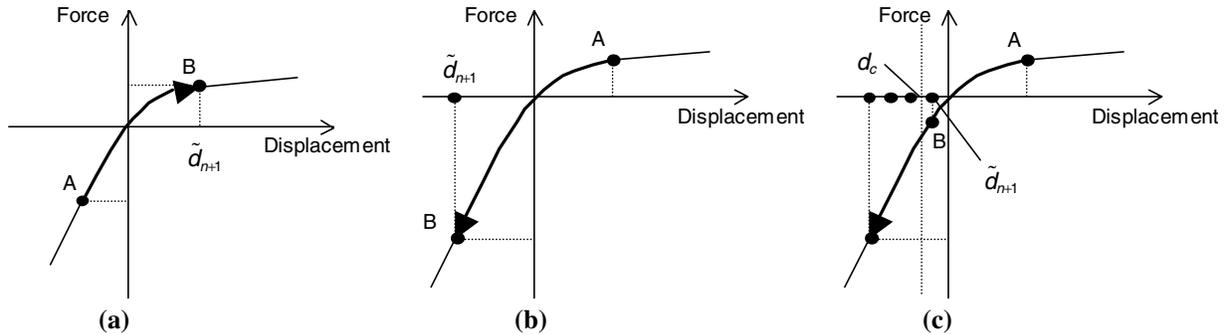
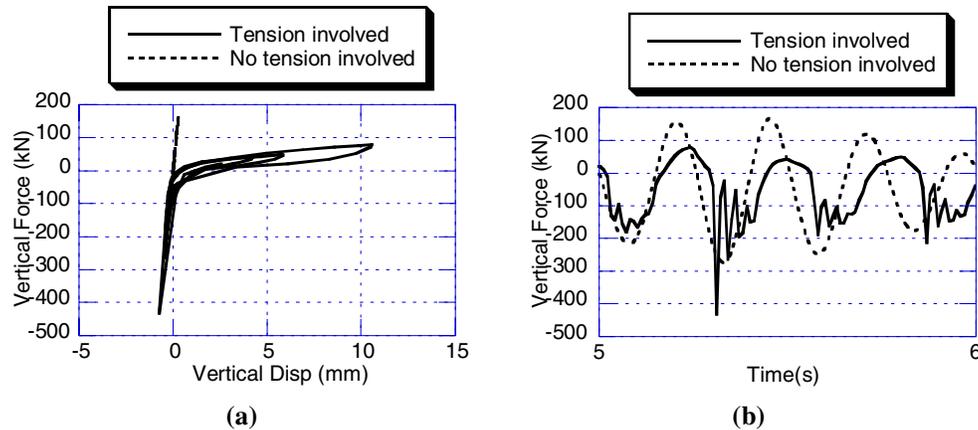


Fig. 7 Implementation of force-displacement switching-control: (a) switching from force to displacement; (b) switching from displacement to force; (c) varying time integration

Online Test Using Displacement-Force Switching-Control

Using the proposed switching-control, two online tests (Tests A and B) were conducted for the simulation of the base-isolated structure when subjected to vertical motion. The vertical component of the JMA record was adopted. In Test A, an initial compressive force of 250 kN was applied on the specimen to simulate the gravity of the superstructure. In Test B, an initial compressive force of 50 kN (instead of 250 kN) was imposed. Because of the smaller initial compressive force, the tested HDBRs sustained significant tensile deformations in Test B, while no tension occurred in Test A. The switching-control was accomplished successfully, with the differences between the predicted and measured values remaining at most 2 % of the largest responses. This demonstrates that the proposed system ensured accurate control even when many rounds of switching between displacement- and force-control took place during the test.

Figure 8(a) compares the hysteresis curves obtained from Tests A and B. The dashed line represents the results of Test A where no tension occurred, and the solid line the results of Test B where tension occurred. For the purpose of comparison, force values obtained for Test A are shifted by 200 kN. Since no tension occurred in Test A, the corresponding force-displacement relationship is linear, while significant plastic deformations occur for a few times in Test B. Figure 8(b) shows the time histories (between 5 and 6 seconds) of the vertical force. In Test A without tension, it vibrates smoothly with a response period of about 0.25 sec, which corresponds to the first natural period of the base-isolated structure. In Test B, the tensile force does not grow because of yielding in tension. Rather high-frequency vibration is notable during the response in compression. This is attributed to bumping that occurred at the instant when the test specimen (base-isolation layer) started taking compression. It is analogous to the situation in which the superstructure throwing into the sky (because the tensile stiffness of the base-isolation layer is very small) falls down and bumps into the ground (because the compressive stiffness of the base-isolation layer is very large). This bumping effect caused large vertical accelerations in the first floor, located immediately above the base-isolators.



**Fig. 8 Responses obtained by online tests with switching-control:
(a) hysteresis curves; (b) force time histories**

CONCLUSION

Major findings obtained from this study are as follows.

1. An online test system that is capable of performing displacement-force mixed-control was developed.
2. Two types of mixed-control, the displacement-force combined-control and the displacement-force switching-control, were devised.
3. The two types of control were applied to the simulation of earthquake responses of a base-isolated structure. The online tests using the controls demonstrated the effectiveness of the proposed methods.

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