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SIMULATIONS ON EFFECTIVENESS OF ENERGY DISSIPATING BUFFER FOR REDUCING RESPONSE OF BRIDGE DURING LARGE EARTHQUAKE

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ABSTRACT

The performance of energy dissipating buffers during large earthquake was simulated. The simulation results show that the relative displacement of bridge girder to the pier can be effectively reduced by using the buffers. The studies on the parameters, such as the gap of buffer, the damping coefficient of buffer were also made and some criteria for design are proposed.

KEYWORDS

Base-isolated Bridge, Large Earthquake, Energy Dissipating Buffer, Displacement Reduction, Non-linear Response, Simulation

INTRODUCTION

During Southern Hyogo Prefecture (Kobe) Earthquake of 17th January 1995 in Japan, many highway and railway bridges were heavily damaged (Obayashi Corp., 1995). One of the countermeasures to reduce

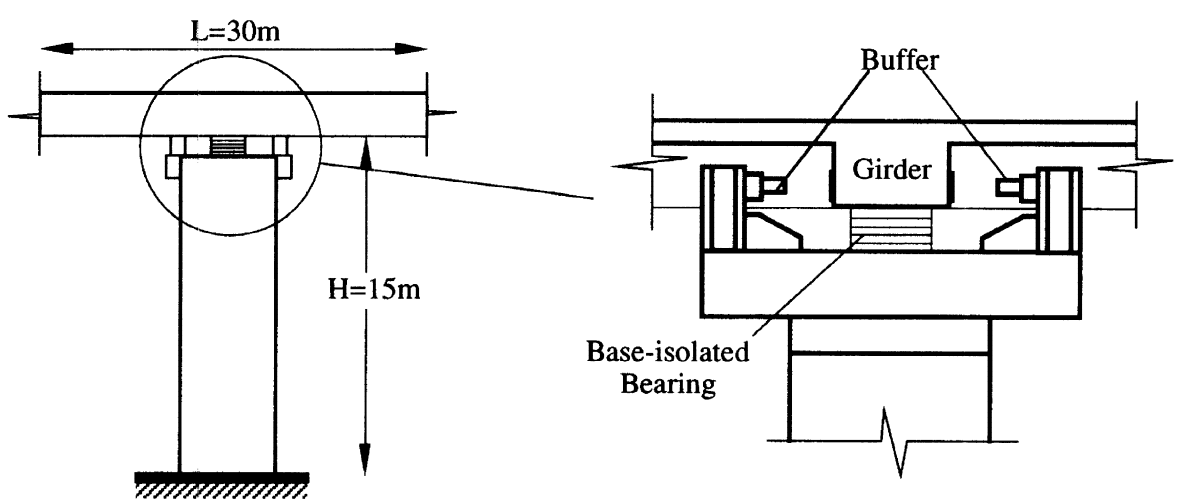

Fig. 1. Model Bridge with Buffers

earthquake forces acting on bridge piers is utilizing isolation bearing to obtain a longer natural period of bridge. Using isolation bearing, however, results in large relative displacement of bridge girder to pier during large earthquake. This large displacement may cause collision of girders and breakage of isolation bearings. Such damages, furthermore, may cause fall-down of upper structures, as found in Kobe Earthquake. The restraint and the reduction of such displacement becomes, therefore, important in the point of view of safety during large earthquake (Moehle, et. al., 1995). In this paper, the authors propose to install energy dissipating buffers to restrict such displacement. The effectiveness of the buffers is investigated on a basis of theoretical simulations.

SIMULATIONS ON PERFORMANCE OF BUFFERS

Bridge Model

A viaduct bridge, about 15 m in height and 30 m in span, is choosen as a typical model for the simulation. Two buffers are installed on the top of pier to restrict the displacement of the girder in the longitudinal direction of the bridge (Fig. 1).

The bridge is modeled as a 2-degree-of-freedom (2DOF) system (Fig. 2). The mass of bridge girder and the mass of pier is 750 ton and 200 ton, respectively. The natural period of bridge is 0.5 sec if the girder is supported by a fixed bearing, while is extended to 2.0 sec if using a isolation bearing (Japan Ministry of Construction, 1992). The structural damping ratio of the pier is 5%, this value takes account of the effects of the dynamic interaction between the foundation of bridge and the soil around. The damping ratio of the isolation bearing is 10%. The restoring force of bridge pier is modeled approximately by a bi-linear elasto-plastic stiffness model (Fig. 2) since the large earthquake is considered in the investigations. The yielding shear force of pier is assumed to be 300 tf. Two buffers, the left one and the right one, are installed. Their displacements relative to the pier are expressed by x_l and x_r, respectively. d expresses the gap between the buffer and the girder.

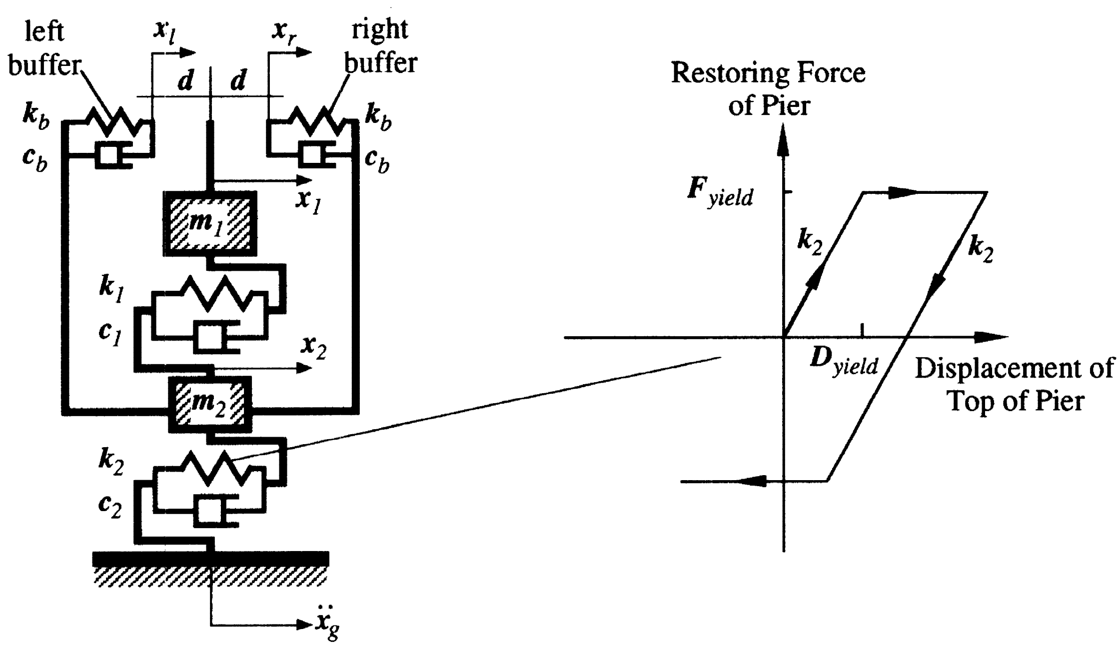

Fig. 2. 2DOF Model for Simulations

Input Ground Motion

The ground motion recorded at the site of Japan Meteorological Agency in Kobe during Kobe Earthquake (Fig. 3) is employed in the simulation. 3 levels of the maximal acceleration are used for different design purpose of the buffers.

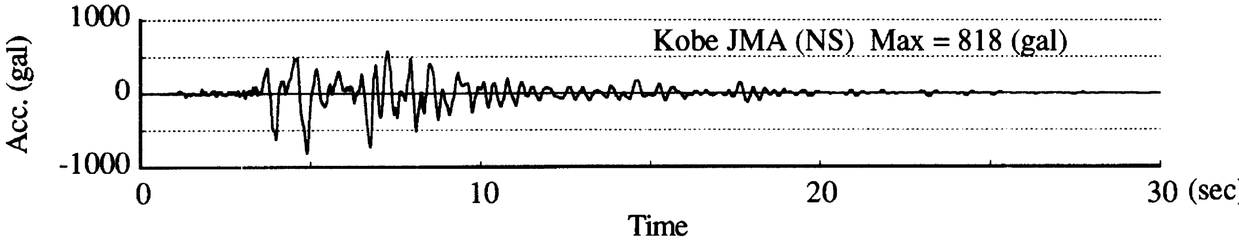

Fig. 3. Input Ground Motion

Level 1 has 300 gal maximal acceleration. The authors propose that elastic response should be ensured for a bridge suffered from this level of earthquake, and the maximal relative displacement of bridge girder should be smaller than a criterion D_1, within which the bridge girder will not come into collision with the buffers. The gap d of the buffer usually has to be not smaller than D_1.

Level 2 has 500 gal maximal acceleration. This level causes larger response of a bridge girder so that the collision with the buffers may happen. The authors suggest that the buffer should be properly designed so that the collision with the buffer will restrict the displacement of girder to be smaller than another criterion D_2, within which collision of girders, breakage of bearing and fall-down of upper-structures are expected to be avoided. In addition, elastic response of bridge pier should be ensured, i. e., there is no structural damage for the bridge.

Level 3 has 818 gal maximal acceleration, as actually recorded at the site during Kobe Earthquake. This level is regarded to be much larger than the input level of the earthquake that had been considered in the design code of Japan. It will cause structural damages so a bridge may loss its function but fall-down of upper-structure is expected to be avoided. So the authors suggest that, under this level of earthquake, the maximal relative

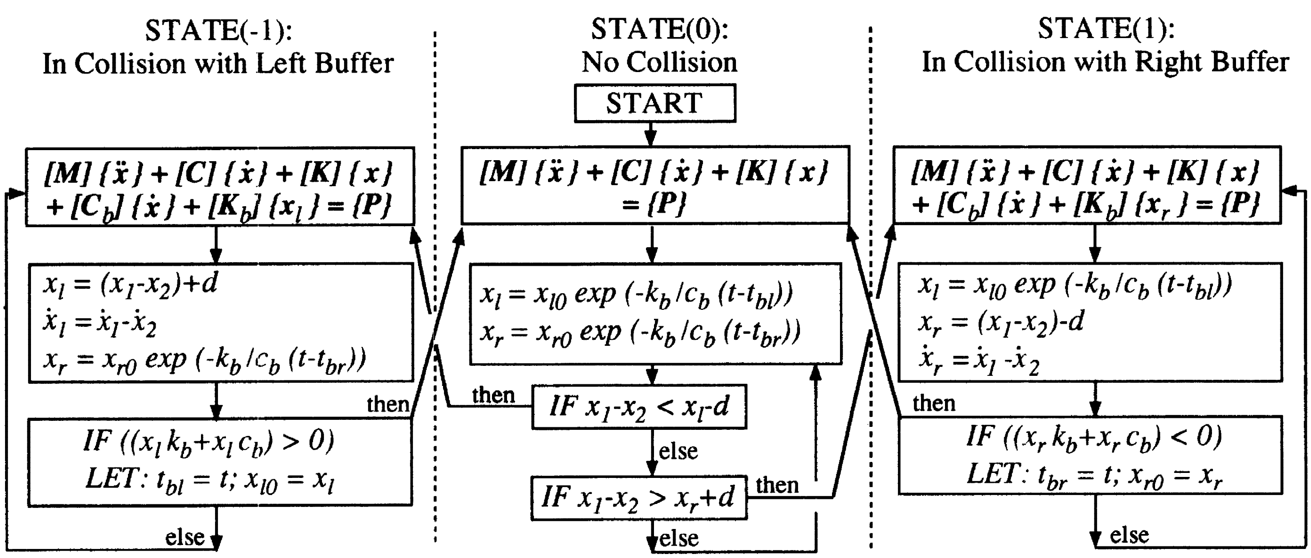

Fig. 4. Flow Chart of Simulation

displacement of girder has to be restricted in the criterion D_2 also, while the ductile response of bridge pier is allowable in the range without significant strength loss of pier.

Theoretical Process

The elasto-plastic response of the model bridge with the buffers is computed. For comparison, the simulations on both a base-isolated bridge without buffers and a ordinary bridge with a fixed bearing are also carried out. The theoretical process of the simulation is shown in Fig. 4.

The response of the bridge is considered to be in one of the 3 states, i.e., STATE (0): no collision and separated from the buffers; STATE (-1): in collision with the left buffer; and STATE (1): in collision with the right buffer. The equations of motion for each state are shown in the flow chart of Fig. 4, where

$$\{\boldsymbol{x}\} = \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix}, \quad \{\dot{\boldsymbol{x}}\} = \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix}, \quad \{\ddot{\boldsymbol{x}}\} = \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} \tag{1}$$

$$[\boldsymbol{M}] = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}, \quad [\boldsymbol{C}] = \begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1+c_2 \end{bmatrix}, \quad [\boldsymbol{K}] = \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1+k_2 \end{bmatrix} \tag{2}$$

$$[\boldsymbol{C_b}] = \begin{bmatrix} c_b & -c_b \\ -c_b & c_b \end{bmatrix}, \quad [\boldsymbol{K_b}] = \begin{bmatrix} k_b & -k_b \\ -k_b & k_b \end{bmatrix} \tag{3}$$

After collision, the buffer, consists of a spring and a dash-pot, will be separated with the girder when the girder's displacement exceeds the peak value and intends to return to the neutral position. The equation of motion for the separated buffer is

$$C_b\, \dot{x}_l + k_b\, x_l = 0 \tag{4a}$$
$$C_b\, \dot{x}_r + k_b\, x_r = 0 \tag{4b}$$

then

$$x_l = x_{l0} \exp\left(-k_b/c_b\,(t - t_{bl})\right) \tag{5a}$$
$$x_r = x_{r0} \exp\left(-k_b/c_b\,(t - t_{br})\right) \tag{5b}$$

where t_{bl} (t_{br}) is the time when the girder separated away from the left (right) buffer, and x_{l0} (x_{r0}) is the displacement of the left (right) buffer at t_{bl} (t_{br}). The mass of the buffer's moving parts is omitted since it is much smaller then the mass of the girder.

The equations of motion are solved by the linear-acceleration step-by-step method (Clough, et. al., 1985). At each step, the state of the structure is determined according to the information of previous step.

The return speed of the buffer to the neutral position is dependent on the ratio of the buffer's damping coefficient of the dashpot to the stiffness of the spring, as can be calculated by equation (5). In this simulation, this ratio is choosen to make that the displacement of buffer due to a collision will return to 10% of the maximal value, x_{l0} (x_{r0}) in a time equaling to the period of the bridge, i. e., 2.0 sec herein, after the separation.

The simulations are carried out for the above model bridge under 3 levels of earthquake input mentioned in previous section. The criteria D_1 and D_2 are determined to be 15.0 cm and 20.0 cm, respectively, for the model bridge. The gap of the buffer, d, is set to be 15.0 cm, which is equal to the criterion D_1. The damping coefficient of the buffer is set to be 20 times of the damping of the isolation bearing of the bridge. This ratio is expressed as a parameter, α, indicating the capacity of energy dissipation of buffer. The effects of d and α on the performance of the buffers are also studied and discussed in the next chapter.

RESULTS AND DISCUSSIONS

Response of Bridge Under Level 1

The responses of two bridges, one is a base-isolated bridge and another is an ordinary bridge with a fixed bearing, are computed (Fig. 5). Under Level 1 earthquake input, the maximal displacement of the girder of the former bridge is 12.0 cm. It is larger than that of the ordinary bridge, 7.2 cm. The shear force of the pier for the ordinary bridge is large and the pier is developed into plastic stage (Fig. 6). By using isolation bearing, the shear force can be reduced to 122.2 tf, which is less than the yielding shear, 300.0 tf, and the response of bridge is ensured in elastic. The maximal relative displacement of girder for the base-isolated bridge is less than the gap, d (=15.0 cm), so there is no collision with the buffers happened.

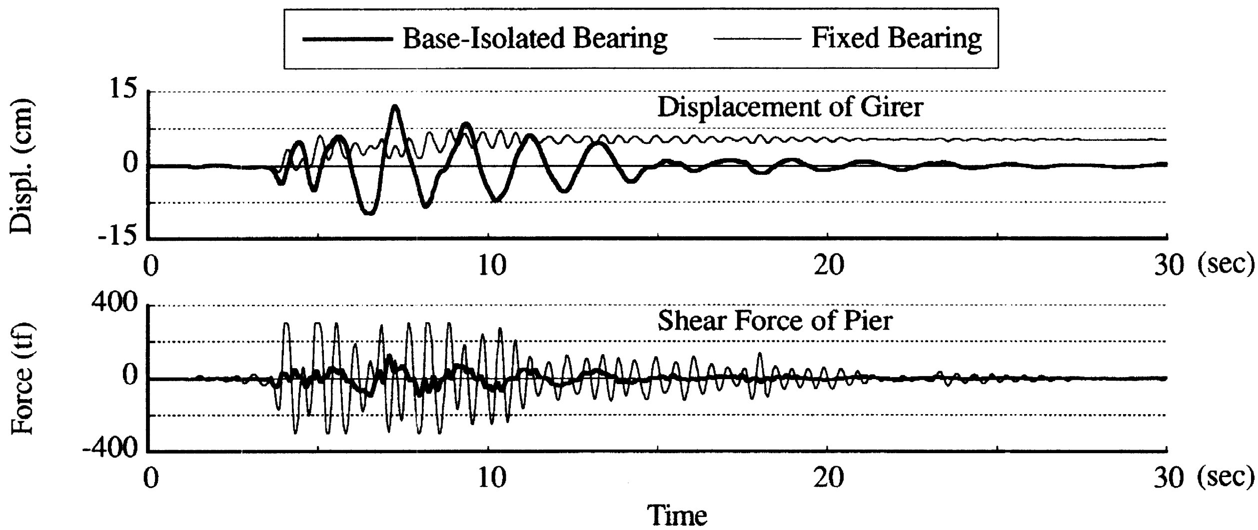

Fig. 5. Response of Bridges Under Level 1 Ground Motion

Response of Bridge Under Level 2

Figure 7 shows the responses of the base-isolated bridge under Level 2 of earthquake input, i. e., the maximal acceleration is 500.0 gal. The maximal relative displacement of the girder is 18.0 cm, larger than D_1 (= 15.0 cm) and smaller than D_2 (= 20.0 cm). The girder has collisions with the buffers at both sides. These collisions partially dissipate the vibrational energy of bridge and restrict the maximal displacement of girder within the criterion D_2. The maximal shear force of pier is 226.3 tf and is smaller than F_{yield}, 300.0 tf. This indicates that the response of bridge is still in elastic stage even the girder had collisions with the buffers.

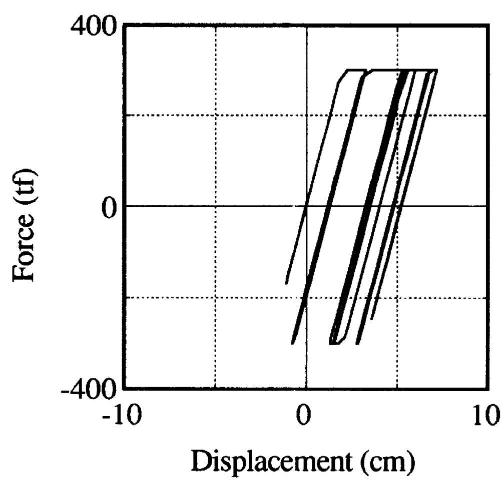

Fig. 6. Displacement - Shear Force Loop (Under Lever 1 Ground Motion)

Response of Bridge Under Level 3

Figure 8 shows the response of the bridge under Level 3 earthquake input. The maximal relative displacement of the girder is 20.0 cm. This is just equal to the criterion D_2. As known from Fig. 8, the girder has collisions

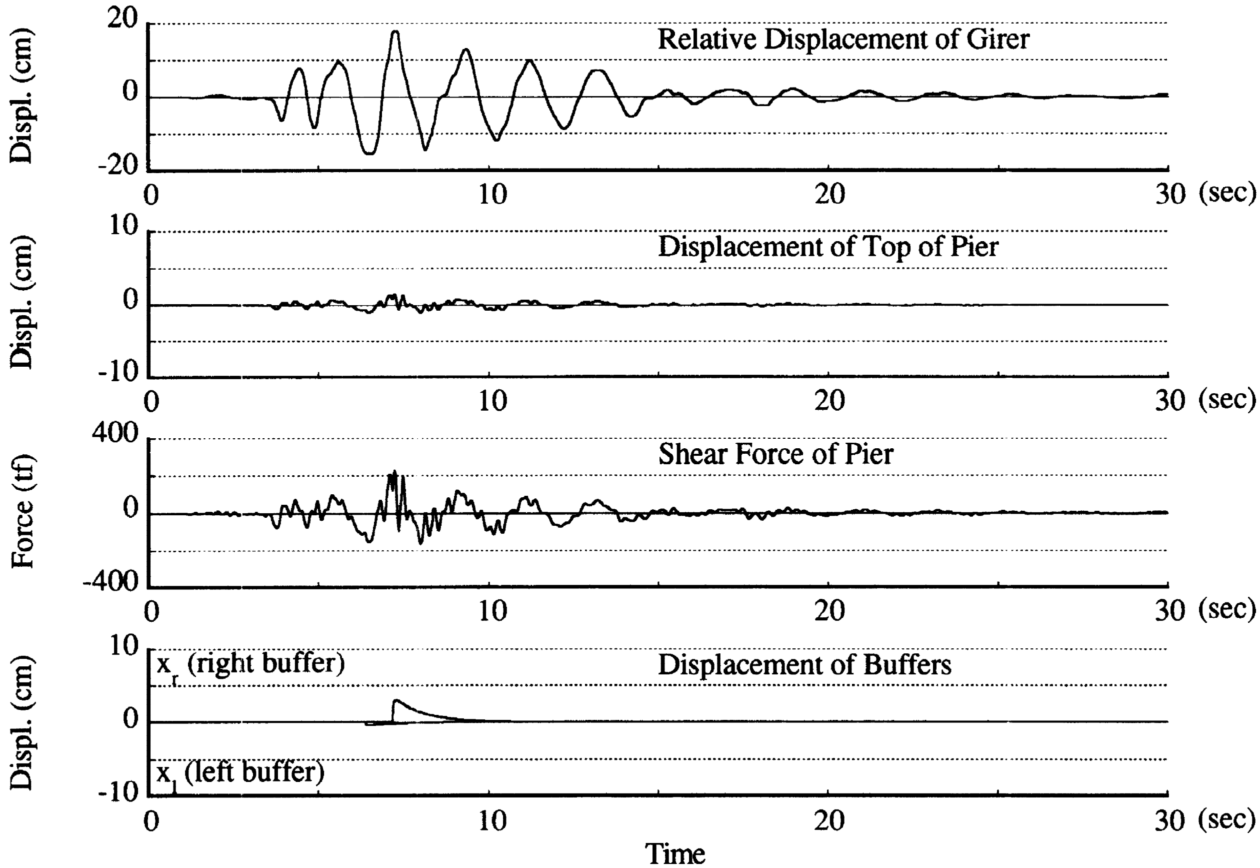

Fig. 7. Response of Bridge with Buffers Under Level 2 Ground Motion

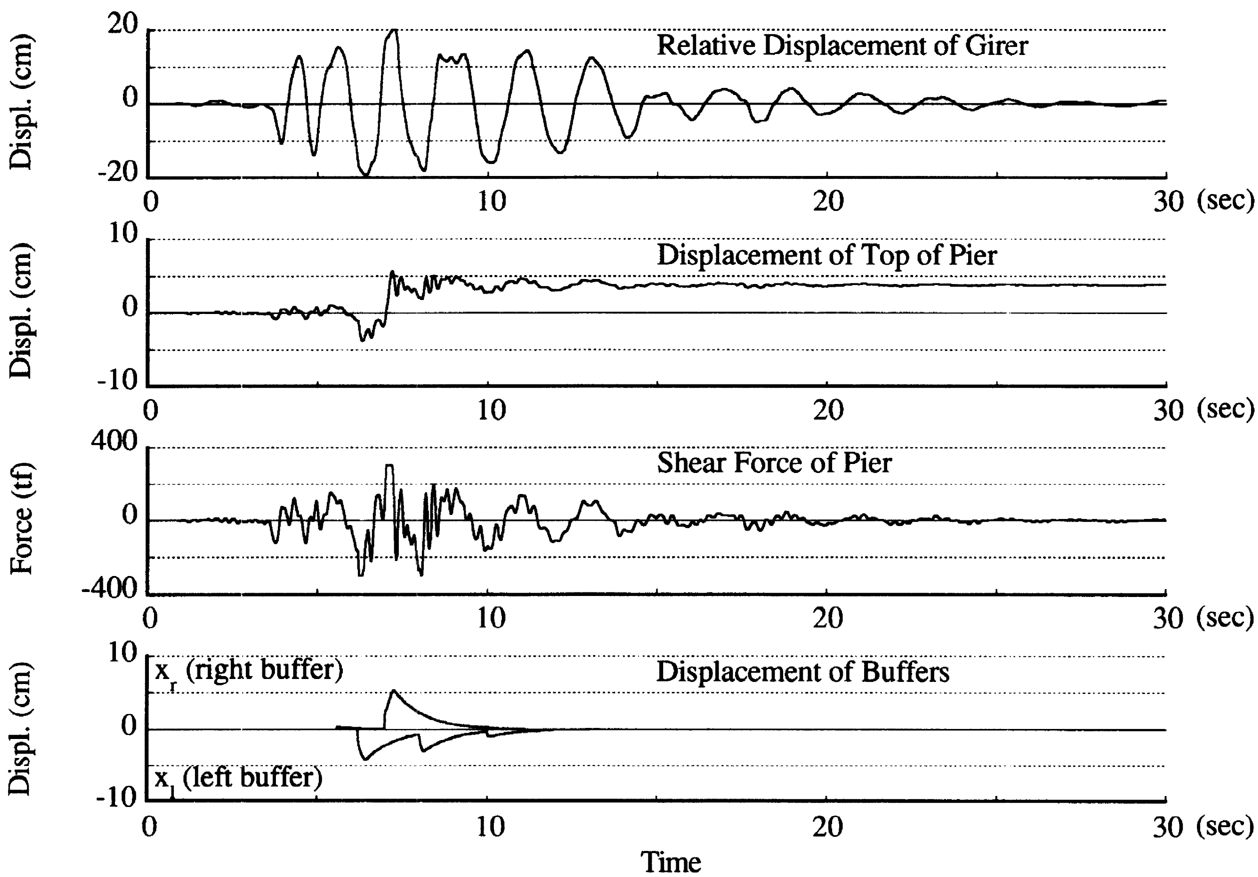

Fig. 8. Response of Bridge with Buffers Under Level 3 Ground Motion

with the buffers at both sides for several times during the earthquake so the displacement of the girder is restricted. The maximal displacement of top of pier is 5.7 cm. There is a 3.7 cm remained displacement at the final, indicating that the response of the pier is into plastic stage already (Fig. 9) since the earthquake input has the maximal acceleration as large as 818 gal. Suffering from such a large earthquake input, it is difficult for the buffers to restrict the relative displacement of girder within the criterion D_2, coincidentally ensuring the elastic response of pier. The partial vibration energy is dissipated by the ductile response of pier.

The displacement of the top of pier at the yielding limit, D_{yield}, is 2.0 cm. The maximal ductile displacement is 5.7 cm, indicating that the related ductility ratio, defined as the ratio of the maximal ductile displacement to D_{yield}, is 2.9. This value indicates that if the bridge pier is designed to have a ductility ratio larger than 3.0, then the pier is possible to support the upper-structure and avoids the fall-down of the girder even the pier may suffer from signifficient damages.

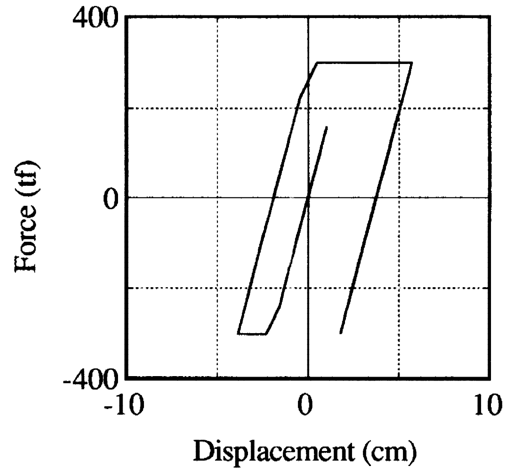

Fig. 9. Displacement - Shear Force Loop (Under Level 3 Ground Mtion)

Effects of α and d

The damping coefficient ratio of the buffer to the isolation bearing, α and the gap of the buffer, d are studied based on the simulations of the response of the model bridge under Level 3 earthquake input. The maximal relative displacement of girder, the maximal displacement of top of pier, the ductility ratio of pier and the energy dissipated due to the ductile response of pier during the earthquake are computed and are listed in Table 1 and Table 2 for various α and various d, respectively. Table 1 shows the effects of α on the performance of buffers. The gap d is 15.0 cm for all cases computed. The damping coefficient ratio α varies from 5 to 30. As increasing of α, the maximal relative displacement of girder is reduced. It is 26.0 cm for $\alpha = 5$ and is 19.4 cm for $\alpha = 30$. This indicates that a larger α results in the better performance of buffer. The responses for all cases are ductile. The maximal ductile displacements of top of pier for each case are not so different and are in the range of 5.2 cm to 6.1 cm, i. e., 2.6 to 3.1 in the ductility ratio. However, one can notice that the total energy dissipated by the ductile response of pier during the earthquake increases definitely as the damping coefficient ratio α increases. This indicates that the pier has to burden more and may suffer from heavier damage when using a larger α.

Table 1 Effects of Damping Coefficient Ratio, α

α	Max. Relative Displ. of Girder (cm)	Max. Displ. of Top of Pier (cm)	Ductility Ratio	Energy Dissipated by Ductile Resp. of Pier (tf-cm)
5	26.0	5.2	2.6	1881.2
10	22.8	6.1	3.1	2726.7
15	21.4	6.1	3.0	3018.6
20	20.0	5.7	2.9	3477.1
25	19.8	5.6	2.8	3683.9
30	19.4	5.5	2.7	3844.0

* maximal Acceleration of Ground Motion: 818.0 gal; Gap of Buffer d: 15 cm.

Table 2 Effects of Gap, *d*

d (cm)	Max. Raletive Displ. of Girder (cm)	Max. Displ. of Top of Pier (cm)	Ductility Ratio	Energy Dissipated by Ductile Resp. of Pier (tf-cm)
5	15.0	(-) 4.6	2.3	5929.3
10	18.6	(-) 5.5	2.8	4026.7
15	20.0	5.7	2.9	3477.1
20	24.6	6.2	3.1	2415.2

* maximal Acceleration of Ground Motion: 818.0 gal; Damping Coefficient Ratio of Buffer α: 20.

Table 2 shows the effects of the gap, d on the performance of buffers. The damping coefficient ratio of buffer, α is 20 for all cases. d ranges from 5.0 cm to 25.0 cm, the maximal relative displacement of the girder related is 15.0 cm and 24.6 cm, respectively. The ductility ratio ranges from 2.3 to 3.1. A smaller gap d results in the better performance of buffers because the effective stork to restrict the displacement of girder is larger, but coincidentally causes the pier to have more burden as listed in Table 2.

When designing buffers for a bridge, the gap, d and the damping coefficient ratio of the buffer, α should be choosen properly according to the earthquake input level, the strength of structure and the displacement criteria of D_1 and D_2 as motioned in previous chapter.

CONCLUDING REMARKS

The simulation results show that the relative displacement of bridge girder to the pier can be effectively reduced by using the energy dissipating buffers. The authors proposed some criteria for design of the buffer and demonstrated the performance of the buffers under different levels of earthquake input by the simulation. It was shown that the buffer can be designed to restrict the displacement of the bridge girder within a certain required range, coincidentally ensuring elastic response of the bridge pier under a medium earthquake. However, under a large earthquake, the partial vibrational energy of bridge has to be dissipated by the ductile response of bridge pier. The parametric studies shows that buffers with a larger damping coefficient or a smaller gap has better performance but the pier has to burden more and may suffer from heavier damage.

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