Analysis of seismic mitigation elastic-plastic passive control for continuous beam bridge*

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ABSTRACT: Two modes of elastic and plastic finite element models for continuous beam bridge are established. Linear viscous fluid dampers are set at the location of the kinetic bearings of bridge. Passive control seismic responses of the bridge are calculated under strong earthquake. Vibration-suppressed effectiveness of passive control for continuous beam bridge under elastic and plastic states is analyzed. The results indicate that the passive control with viscous fluid dampers can get good vibration-suppressed effectiveness for both elastic and plastic seismic responses of bridge. But vibration-suppressed effectiveness of dampers under plastic state is less than that under elastic state. Plastic passive control seismic responses of bridge are less than elastic passive control seismic responses with piers getting into plastic state under strong earthquake. The seismic mitigation control system of bridge designed with calculation of elastic mode can satisfy the requirement of seismic mitigation control with piers getting into plastic state.

KEYWORDS: elastic, plastic, passive control, continuous beam bridge, vibration-suppressed effectiveness

1 PREFACE

Earthquakes are serious natural disasters menacing the human being. The bridge is transportation hinge and important lifeline engineering, and its characteristic of seismic mitigation is paid attention to by the bridge engineers. Fixed bearings are set on a pier in each unit for long-span continuous beam bridge and kinetic bearings are set on the other piers. Under strong earthquakes the fixed bearings of a unit are endured the most longitudinal seismic action with kinetic bearings slipping, so the fixed piers with fixed bearings are easy to be destroyed. The structural control technique is an effective method to enhance aseismatic ability of bridge. Some control devices are set at the positions of bridge. When the bridge vibrates, these devices can passively or actively add some control force or adjust the dynamic characteristic of structure, so the seismic responses of bridge are reduced evidently. The passive control does not need external energy, and consumes or transfers vibration energy by vibration mitigation device. It has the advantages of simple constitution, low price and easy maintenance and is applied widely. From the view of energy, passive control with dampers reduces seismic responses of bridge by dampers consuming energy. Usually the design rule of energy consumed seismic mitigation is that the main structures are still in elastic state in strong earthquake[1], that is, control devices can offer enough damping to the bridge structure to consume energy, then bridge in strong earthquake is basically still in elastic state to protect

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the structure. For the randomicity and abruptness, earthquake intensity can not be predicted correctly. When strong earthquake comes, the bridge structure with passive control dampers can also be in the plastic state. For the continuous bridge with passive control dampers, the fixed piers can be in plastic state during strong earthquake. So the characteristics of piers in two states of elasticity and plasticity are worthy of studying systemically with passive seismic mitigation dampers, and some guide and advice can be presented for the wide application of seismic mitigation with dampers in bridge engineering.

In this paper, bridge with dampers being in plastic state during strong earthquake, the elastic and plastic seismic response passive control calculation is performed with total finite element model for a long span continuous bridge. The characteristic of vibration-suppressed effectiveness and seismic response is analyzed for continuous bridge with passive dampers when the bridge is in elastic and plastic states.

2 CALCULATION APPROACH OF ELASTIC AND PLASTIC SEISMIC RESPONSE FOR BRIDGE

If r semi-active varying damping control devices were set on a structure with n free degrees, the kinetic equation of structural semi-active control system with ground motion uniform input is[7]:

$$M\ddot{X}(t)+C(t)\dot{X}(t)+K(t)X(t)=B_0U(t)+H_0M\ddot{X}_g(t) \qquad X(t_0)=X_0 \quad \dot{X}(t_0)=\dot{X}_0 \tag{1}$$

In the formula, M , $C(t)$ and $K(t)$ is $n\times n$ dimension structural mass matrix, damping matrix and stiffness matrix respectively. $X(t)$, $\dot{X}(t)$ and $\ddot{X}(t)$ is n dimension structural displacement array, velocity array and acceleration array respectively. $\ddot{X}_g(t)$ is ground motion acceleration. $\mathrm{U}(t)$ is r dimension control force array. H_0 is n dimension ground motion acceleration position array. B_0 is $n\times r$ dimension semi-active control damper position matrix.

The relationship between control force $u_i(t)$ and damping force $f_{id}(t)$ is $u_i(t)=-f_{id}(t)$. In this paper linear viscous dampers are used to analyze seismic response of bridge under longitudinal ground motion input. Damping force of linear viscous damper is $f_{id}(t)=c_{id}\dot{y}_{is}(t)$, in which c_{id} is viscous damping coefficient of damper and $\dot{y}_{is}(t)$ is the relative velocity corresponding damper position of structural passive control system.

3 CALCULATION MODEL OF BRIDGE

A long span continuous bridge with span combination of 110+2×200+110 meters, section of beam is single box single room, and piers are hollow thin wall. Three piers are all

30 meters high. Bearings are basin rubber bearings. Fixed bearings are set on the top of the middle pier of NO. 2, and sliding bearings are set on the tops of other two piers of NO. 1 and NO.3 and on the top of the 2 abutments. Foundations are rigid expending root. Beam and piers are all concrete of c50 and steel bars in piers are Ⅱ steel bar. In the finite element model, the bearings are simulated with freedom degree principal and subordinate, and bottoms of piers are rigid fixed. Beam is simulated with spatial elastic beam element and piers are simulated with spatial elastic and plastic beam element. The finite element model includes 24 elements, 28 nodes and 155 freedom degrees. The finite element model of continuous bridge is shown in figure 1.

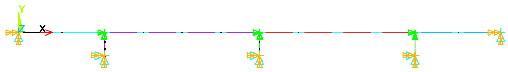
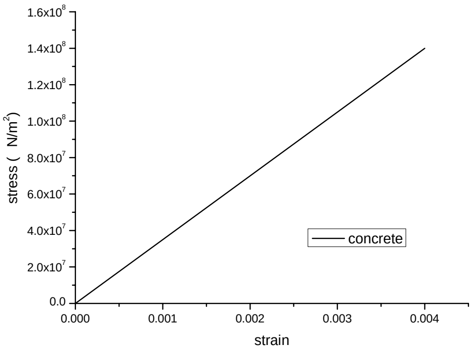


Fig. 1 finite element calculation model of continuous bridge

In strong earthquake, the fixed piers of bridge may be in plastic state. In this paper, 2 calculation modes of elasticity and plasticity are adopted to calculate the seismic response of bridge. One calculation mode is that un-controlled piers without dampers and controlled piers with dampers are all in elastic states. The elastic constitutive model of concrete for piers is shown in figure 2, and elastic constitutive model of steel bar for piers is shown in figure 3.



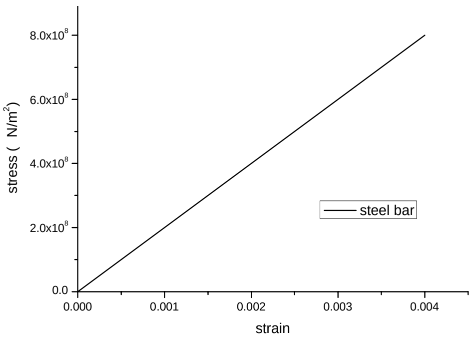
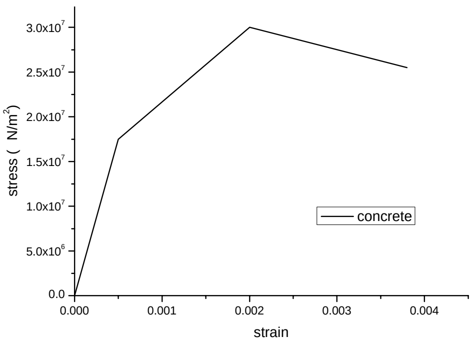


Fig.2 elastic constitutive model of concrete fig. 3 elastic constitutive model of steel bar



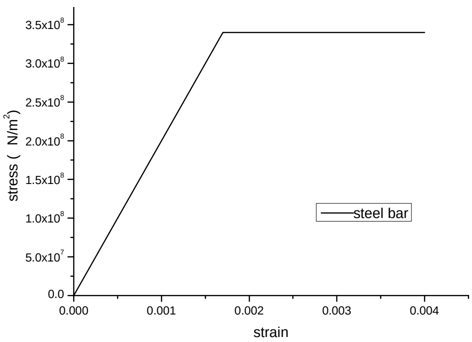


Fig.4 elastic and plastic constitutive model of concrete fig. 5 elastic and plastic constitutive model of steel bar

Another calculation mode is that un-controlled piers without dampers and controlled piers with dampers are all in plastic states. The elastic and plastic constitutive model of concrete for piers is shown in figure 4, and elastic and plastic constitutive model of steel bar for piers is shown in figure 5.

Elastic and plastic fiber element of beam and column is used to simulate the elastic and plastic nonlinear characteristics of piers. Elastic and plastic fiber beam element is divided to some segments, and the characteristic of each segment is represented by middle section. Sections are further divided many rectangle grids which can be concrete of steel bar. In the calculation, bending stiffness of each section is got by plane section suppose and relationship of strain and stress for concrete and steel bar, then the element stiffness is got by integral along element length.

4 CALCULATING RESULTS OF SEISMIC MITIGATION CONTROL

The ground motion input is EL Centro ground motion time history (NS, May, 18, 1940). Its peak acceleration is 341.7 gal with main period of 0.55 seconds. The ground motion acceleration time history curve is shown in figure 6. In order to make the fixed piers of bridge into plastic state under earthquake action, the peak acceleration of ground motion is adjusted with 400 gal.

Dampers locate at the position of sliding bearings on the top of abutments and piers. Four groups of dampers are set on the whole bridge with linear viscous damping coefficient of $2.0\times10^{6}\,N\cdot s/m$. When the peak acceleration of ground motion is 400 gal, the NO. 2 pier is in elastic state with un-controlled or controlled bridge for NO. 1 calculating mode, and the NO. 2 pier is in plastic state with un-controlled or controlled bridge for NO. 2 calculating mode.

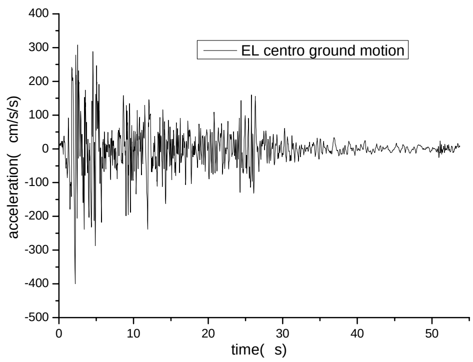


Fig. 6 acceleration of EL Centro ground motion

In order to scale the decreasing amplitude effect of semi-active control system, the concept of decreasing amplitude ratio is induced. Its value is defined according to seismic responses of bridge structure as following: $JZ_i=\frac{d_i^u-d_i^c}{d_i^u}\times100\%$. In the formula, JZ_i is decreasing amplitude ratio of i free degree. d_i^u and d_i^c are seismic responses of i free degree of bridge without dampers and with dampers respectively, which is the maximal response of mean square root response during the ground motion action. The mean square root (MSR) response is defined as $\|\bullet\|=\sqrt{\frac{1}{t_f}\int_0^{t_f}(\bullet)dt}$, in which t_f is durative time of ground motion.

The maximal seismic response and mean square root seismic response is shown in table 1 when peak acceleration of ground motion is 400 gal. Maximal longitudinal displacement of beam at the top of number 2 pier is D2. Maximal longitudinal displacement of pier at the top of number 1 pier is D1. Maximal longitudinal acceleration of beam at the top of number 2 pier is A2. Maximal longitudinal acceleration of pier at the top of number 1 pier is A1. Maximal moment at the bottom of number 2 pier is M2. Maximal moment at the bottom of number 1 pier is M1. Maximal shear force at the bottom of number 2 pier is Q2. Maximal shear force at the bottom of number 1 pier is Q1.

From table 1 some conclusions can be got as following: (1) passive control with viscous dampers can get good vibration-suppressed effectiveness for elastic and plastic seismic responses of bridge. (2) vibration-suppressed effectiveness of plastic passive control is less than that of elastic passive control. (3) when the pier gets into plastic state in strong earthquake, some seismic energy is consumed by plasticity. The plastic seismic response is less than elastic seismic response for both un-control bridge and control bridge.

Tab.1 seismic response of bridge

seismic response		elastic un-control	elastic control	JZ_i	plastic un-control	plastic control	JZ_i
D2(m)	maximal	0.280	0.214	24%	0.259	0.211	19%
	MSR	0.131	0.094	29%	0.116	0.089	23%
D1(m)	maximal	0.0448	0.0408	9%	0.0448	0.0408	9%
	MSR	0.0147	0.0113	23%	0.0147	0.0112	23%
A2(m/s^2)	maximal	3.40	3.48	-2%	3.42	3.49	-2%
	MSR	1.11	1.05	6%	1.08	1.04	3%
A1(m/s^2)	maximal	10.08	8.28	18%	10.07	8.29	18%
	MSR	2.65	1.68	37%	2.65	1.68	37%
M2 (MN.m)	maximal	775.16	594.88	23%	637.14	536.60	16%
	MSR	367.27	260.97	29%	315.87	247.56	22%
M1 (MN.m)	maximal	155.56	138.24	11%	155.58	138.22	11%
	MSR	48.83	36.52	25%	48.83	36.43	25%
Q2(MN)	maximal	25.64	20.32	21%	21.53	18.87	12%
	MSR	12.43	8.80	29%	10.68	8.35	22%
Q1(MN)	maximal	9.28	7.92	15%	9.26	7.91	15%
	MSR	2.51	1.91	24%	2.51	1.90	24%

In order to compare seismic response of bridge with 4 states of elastic un-control, elastic control, plastic un-control and plastic control, longitudinal displacement at top of pier, moment at bottom of pier and shear force at bottom of pier are drawn and shown in figure 7 to figure 9 for number 2 pier.

From figure 7 to figure 9 it can be seen that seismic responses decrease in turn according to the 4 states of elastic un-control, plastic un-control, elastic control and plastic control. The seismic response with plastic control pattern is the least. So the seismic mitigation system of passive control bridge designed with elastic state is more conservative and the system can satisfy the requirement of seismic mitigation control with pier being in plastic state during the action of strong earthquake. In the actual engineering, seismic mitigation passive control system can be designed with elastic state for continuous bridge. This can make the design of seismic mitigation passive control system for bridge easy.

The hysteretic curve of dampers at abutment and pier is shown in figure 10- figure 11, in which energy consumed by dampers is shown in the two states of elastic and plastic states.

From the figure 10- figure 11 it is can be seen that hysteretic curves of dampers with states of elastic control and plastic control are very closely after dampers are set at the positions of abutments and piers, and they are all plump. It indicates that dampers in both elastic and plastic states can consume much energy. Energy consumed by dampers at abutments in two states of elasticity and plasticity is $1.04914MN.m$ (elastic) and $0.98221MN.m$ (plastic), respectively. Energy consumed by dampers at abutments in plastic state is 94% of that in elastic state. Energy consumed by dampers at piers in two states of elasticity and plasticity is $1.39565MN.m$ (elastic) and $1.32864MN.m$ (plastic), respectively. Energy consumed by dampers at piers in plastic state is 94% of that in elastic state. It can be shown that energy consumed by dampers in plastic state is less than that in elastic state. This is the reason why vibration-suppressed effectiveness of passive control in plastic state is less than that of passive control in elastic state.

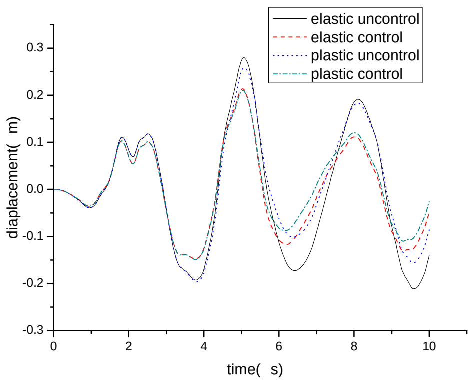


Fig. 7 longitudinal displacement at top of pier 2

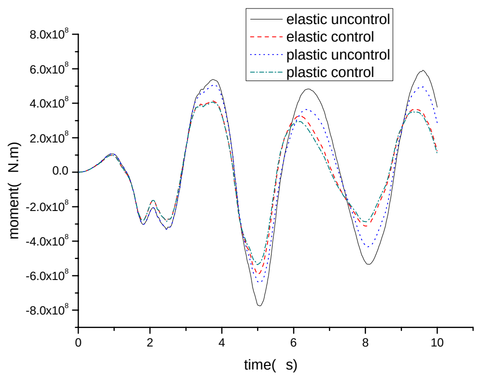


Fig. 8 moment at bottom of pier 2

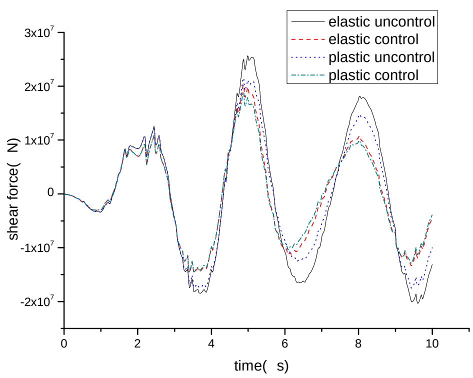


Fig. 9 shear force at bottom of pier 2

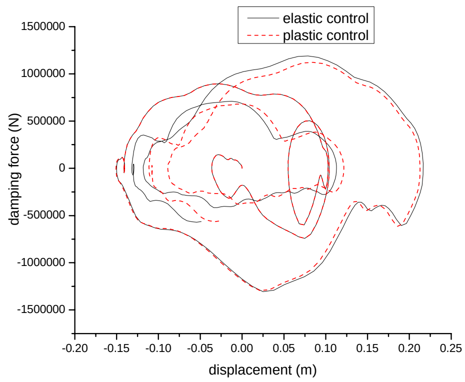


Fig. 10 hysteretic curves of dampers at abutment

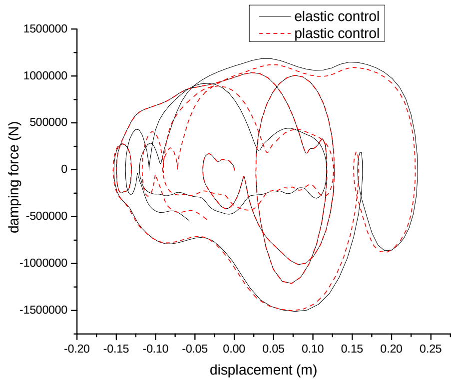


Fig. 11 hysteretic curves of dampers at pier

5 CONCLUSIONS

In this paper, seismic passive control numerical simulation is performed with spatial finite element model of bridge under strong earthquake for a long span continuous bridge. Through calculation and analysis of seismic passive control for the continuous in elastic and plastic state, some conclusions can be got as following:

(1) Passive control with viscous dampers can get good vibration-suppressed effectiveness for elastic and plastic seismic responses of bridge. Energy consumed by dampers in plastic state is less than that in elastic state. Vibration-suppressed effectiveness of dampers in plastic state is less than that of passive control in elastic state.

(2) Piers being in plastic state under strong earthquake makes seismic responses of bridge less. The seismic mitigation system of passive control bridge designed with elastic state can satisfy requirement of seismic mitigation control with piers being in plastic state. This can make the design of seismic mitigation passive control system for bridge easy.

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REFERENCES:

[1] ZHOU Fu-lin. (1997). engineering structure seismic mitigation control. Earthquake Press. (in Chinese).

[2] OU Jin-ping. (2003). Structural vibration control--active, semi-active and intelligent control. Science press. (in Chinese).

[3] HU Yu-xian. (1988). Earthquake engineering. Earthquake Press. (in Chinese).

[4] FAN Li-chu.(1997). Earthquake resistant for bridge. Tongji University Press. (in Chinese).

[5] QI Xing-jun, LI Xiao-jun, ZHOU Guo-liang. (2006). Analysis on influence of seismic

traveling wave effect on semi-active control for long-span rigid-continuous bridge, Acta Seismologica Sinica. 19(2):199-206

[6] T. Y. LEE, K. KAWASHIMA. (2004) EFFECTIVENESS OF SUPPLEMENTARY DAMPERS FOR ISOLATED BRIDGES UNDER STRONG NEAR-FIELD GROUND MOTIONS, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1-6, Paper No.138

[7] QI Xing-jun. (2006). Study on seismic semi-control for bridges. Doctoral thesis of institute of geophysics China earthquake administration.

[8] CHEN Guang-ming; WANG Dan-hua; CHEN Zhi-jun; DENG Ge. (2004). Study on the Nonlinear Seismic Behavior of a Cable-stayed Bridge. Journal of Wuhan University of Technology, 26(4):56-59

[9] Wang Luoying, Zheng Yu. (2005). Elastic and Plastic Anti-Seismic Analysis of Reinforced Concrete Column Type Piers. Urban Roads Bridges & Flood Control, (6):53-55

[10] WANG Li; YAN Gui ping; FANG You liang. (2002). Nonlinear Seismic Response Analysis of Isolation Bridges. Journal of Northern Jiaotong University, 26(1):80-84

[11] NIE Li-ying, LI Jian-zhong, HU Shi-de, FAN Li-chu. (2004). Nonlinear Analysis and Seismic Estimation on Curved Beam Bridge. Journal of Tongji University, 32(10):1360-1364