Analysis of seismic response control for long-span cable-stayed bridge under traveling wave input*

QI Xing-jun[1], LI Xiao-jun[2]

([1] Associate Professor, School of Civil Engineering, Shandong Jianzhu University, Jinan, China)

([2] Professor, Institute of Engineering Mechanics, China Earthquake Administration, Harbin, China)

E-mail: qxj123@163.com

ABSTRACT: In order to study the influence of traveling wave effect on control effectiveness of seismic mitigation for cable-stayed bridge. The vibration-suppressed effectiveness of semi-active control and passive control for a long-span floating cable-stayed bridge is calculated and analyzed with its three dimensional finite element model. The seismic responses of cable-stayed bridge under traveling wave input are calculated. Semi-active control and passive control can get good control efficiency for the most seismic responses of the cable-stayed bridge, but they can make some seismic responses including axial force of the beam lager. The seismic inputs with different frequency spectrums evidently influence seismic responses of the cable-bridge and vibration-suppressed effectiveness of the control methods. Semi-active control is better than passive control with most damping force all along for vibration-suppressed effectiveness of the integer seismic responses after traveling wave effect considered. Traveling wave effect can make bad influence on the beam of cable-bridge, but can be propitious to bridge tower. Bad influence of traveling wave effect on vibration-suppressed effectiveness of the two control methods is not remarkable.

KEYWORDS: cable-stayed bridge, traveling wave effect, vibration-suppressed effectiveness, semi-active control, passive control

1 PREFACE

In analysis of seismic response for long-span cable-stayed bridge, much uncertainty exists in ground motion input and is the weakest part in seismic design. Ground motion input method is usually uniform input. But its calculating result has much difference from the actual situation for long-span cable-stayed bridge. When earthquake happens, the ground motion inputs at supports of long-span cable-stayed bridge are different for the influence of traveling wave effect. So the multiple supports input must be considered in seismic responses analysis for long-span cable-stayed bridge[5]. Many researchers have got the conclusion that seismic responses of long-span cable-stayed bridge have relation to not only the ground motion input but also the bridge structure characteristic. The uniform ground motion input can not determine seismic design for long-span bridge. Seismic response analysis with multiple excitations for long-span bridge is important in evaluating the seismic characteristic of bridge with ground motion field changing spatially considered. For the long-span bridge with seismic mitigation devices, multiple excitation can not be ignored[7].Liquid viscid damper can not produce additive force in beam for temperature change and concrete shrink. It can bring much damping force and consume the energy imported into bridge by earthquake to reduce

*Supported by National Science and Technology Supporting Plan of China (NO.2006BAC13B02), National Natural Science Foundation of China (NO.50708100)

seismic responses of bridge. Liquid viscid damper is good vibration decreasing device for long-span cable-stayed bridge.

In this paper, influence of traveling wave effect considered, calculation and analysis of seismic response semi-active control and passive control are performed with liquid viscid damper for a long-span floating cable-stayed bridge with its three dimensional finite element model. The vibration-suppressed effectiveness of semi-active control for long-span cable-stayed bridge is discussed under seismic traveling wave input.

2 CALCULATION MODEL FOR CABLE-STAYED BRIDGE

One long-span floating cable-stayed bridge with accessorial piers, its span combination is 48+204+460+204+48 meters and the total length is 964 meters. Bridge width is 36.3 meters, and the 2 towers are 161.4 meters high. Additive piers are set in side span. Main beam is steel structure and tower is prestressed concrete structure. The cable is made of high strong steel wire zinced. Dual directional sliding longitudinal bearings and transverse wind bearings are set at the position of tower. Single directional longitudinal sliding bearings are set at additive piers and transitional piers to restrict transverse displacement of beam.

The three dimensional finite element model is established. Beam and tower are simulated with spatial beam element. Cable is simulated with cable element and each cable is one cable element. Bearings are simulated with freedom degree released. There are 162 elements, 162 nodes and 532 freedom degrees. Its finite element calculation model is shown in figure 1.

Characteristic of the cable-stayed bridge is calculated. Its first vibration mode is longitudinal floating with period of 9.84 seconds. The former 4 vibration mode of cable-stayed bridge is shown in figure 2.

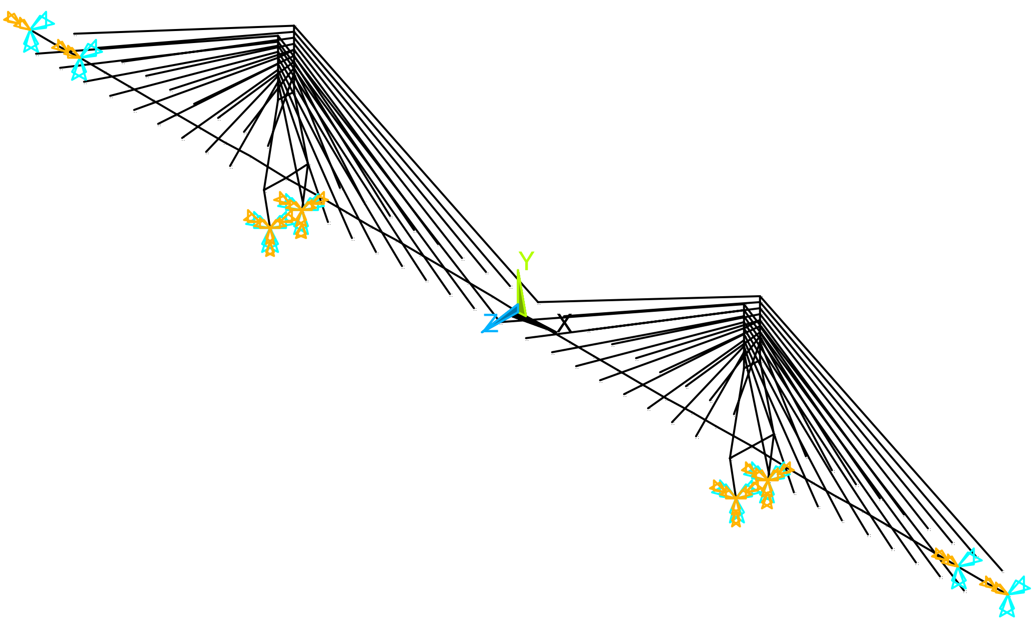
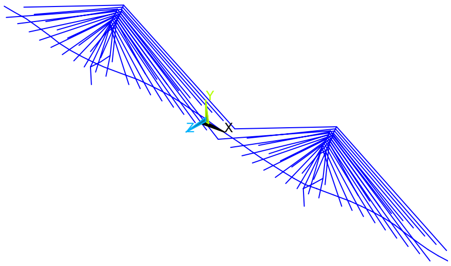
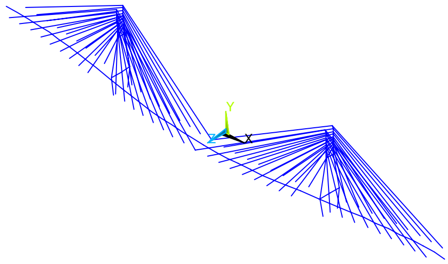


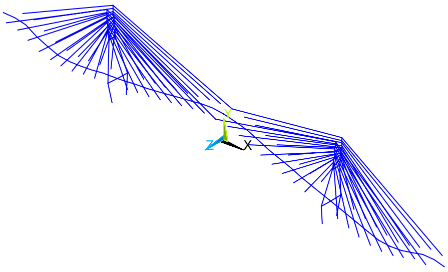
Fig. 1 finite element calculation model for cable-stayed bridge



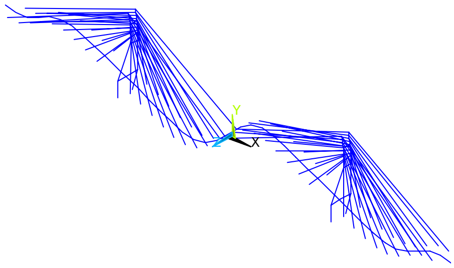
First mode T_1 =9.84s



second mode T_2 =4.65s



Third mode T_3 =2.63s



fourth mode T_4 =1.96s

Fig. 2 vibration mode of bridge

3 GROUND MOTION INPUT

In order to analyze the influence of different ground motions on seismic response control for long-span cable-stayed bridge, two actual ground motion acceleration records are chosen which are Northridge ground motion (1994/01/17, peak acceleration is 460.1gal) and Duzce ground motion (1999/11/12, peak acceleration is 37.2 gal), respectively. Peak acceleration of the ground motions are adjusted of 300gal. Acceleration time history curves of the 2 ground motions are shown in figure 3. Response spectrums of the ground motions are shown in figure 4.

From figure 4 it is can be seen that classic period of Northridge ground motion and Duzce ground motion is 0.28 second and 1.7 second, respectively, and Duzce ground motion has more long periods than Northridge ground motion. The 2 ground motions are representative.

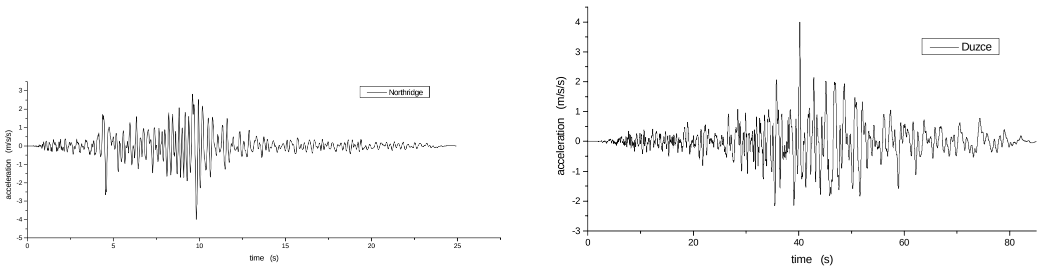


Fig. 3 two ground motion accelerations

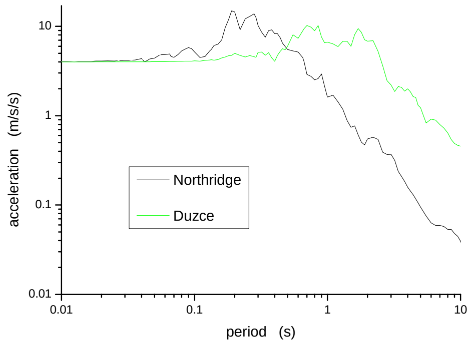


Fig. 4 acceleration response spectrums of the 2 ground motions

Ground motion input is traveling wave input in this paper to consider the influence of multiple excitation on seismic response of bridge. The ground motions input at the piers are same, but they lag some time in turn. The delay time of ground motion input for each pier is calculated based on instance of the two towers with seismic traveling wave velocity of 500m/s. Then seismic response of bridge is calculated under traveling wave input.

4 CONTROL METHODS FOR CABLE-STAYED BRIDGE

The kinetic equation of l non-supported nodes for bridge structure can be expressed as state equation as following:

$$\dot{Z}(t)=AZ(t)+BU(t)+H\ddot{X}_b(t)+H_v\dot{X}_b(t) \qquad Z(t_0)=Z_0 \tag{1}$$

In the formula , $Z=\begin{bmatrix} X_s^d \\ \dot{X}_s^d \end{bmatrix}$, $A=\begin{bmatrix} 0 & I \\ -M_{ss}^{-1}K_{ss} & -M_{ss}^{-1}C_{ss} \end{bmatrix}$, $B=\begin{bmatrix} 0 \\ M_{ss}^{-1}B_0 \end{bmatrix}$,

$H=\begin{bmatrix} 0 \\ K_{ss}^{-1}K_{sb}-M_{ss}^{-1}M_{sb} \end{bmatrix}$, $H_v=\begin{bmatrix} 0 \\ M_{ss}^{-1}C_{ss}K_{ss}^{-1}K_{sb}-M_{ss}^{-1}C_{sb} \end{bmatrix}$. X is structural displacement array and U is control force array. B_0 is location matrix of dampers. Subscript s denotes non-supported nodes of bridge structure and b denotes supported nodes. $\ddot{X}_b$ and $\dot{X}_b$ is ground motion acceleration and velocity of supported nodes of bridge, respectively.

Viscous dampers are adopted as vibration control device. The positions are connect part of tower and beam, connect part of additive pier and beam and connect part of transitional power and beam. There are 6 groups of dampers on the total bridge. The relationship between semi-active control force $u_{is}(t)$ and semi-active damping force $f_{id}(t)$ is $u_{is}(t)=-f_{id}(t)$. 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 semi-active control system. The limited continuous control algorithm is adopted as following which can well pursue the effect of active control (semi):

Semi-active control algorithm (semi)： $f_{id}=\begin{cases} f_{id\max} & (u_i\dot{y}_{is}<0且|u_i|\geq f_{id\max}) \\ |u_i|\operatorname{sgn}(\dot{y}_{is}) & (u_i\dot{y}_{is}<0且|u_i|<f_{id\max}) \\ f_{id\min} & (u_i\dot{y}_{is}\geq 0) \end{cases}$ (2)

When semi-active control damping force is always the maximal damping force, semi-active control can be passive control.

Passive control algorithm (p-on): $f_{id}=f_{idy\max}\operatorname{sgn}(\dot{y}_{is})$ (3)

The classic optional control arithmetic LQR with full state feedback is adopted. The right matrix Q and R are $Q=\alpha\begin{bmatrix} K_s^d & 0 \\ 0 & M_s^d \end{bmatrix}$ and $R=\beta I$, respectively with $\alpha=1.0\times10^3$ and $\beta=1.0\times10^{-3}$. The active control force of bridge is got by calculation. Maximal semi-active control force is made to be equal to maximal active optimum control force. Maximal damping coefficients of each viscous damper is got which is $c_{\max}=3.25\times10^6 N.s/m$ at the additive pier and $c_{\max}=6.53\times10^6 N.s/m$ at the tower. The adjustable multiple of damping force of semi-active control damper is 8, then the minimal viscous damping coefficient of each damper is got. With semi-active control algorithm and passive algorithm, seismic response of bridge is calculated under ground motion uniform input and traveling wave input.

5 CALCULATION RESULT OF VIBRATION CONTROL

This cable-stayed bridge is longitudinal floating system. Longitudinal displacement of beam is greater under ground motion action and is the main control goal of seismic mitigation. Seismic responses of towers and beam are selected to be output which including longitudinal X direction displacement of nodes, moment of element circling transverse Z direction , shear force and axial force of X direction. The nodes output are as following:

(1) displacement: node 21 at top of left tower (longitudinal displacement Dx21), node 102 at top of right tower (longitudinal displacement Dx102), node 20 at middle of beam (longitudinal displacement Dx20).

(2) Internal force (moment, shear force and axial force): node 32 at bottom of left tower (moment M32、shear force Q32), node 113 at bottom of right tower (moment M113、shear force Q113), node 20 at middle of beam (moment M20、axial force N20).

In order to scale the decreasing amplitude effect of dampers, the concept of decreasing amplitude ratio is induced. Its value is defined according to seismic responses of bridge structure as following: $JZ_i=\frac{\left|d_i^u(t)\right|_{\max}-\left|d_i^c(t)\right|_{\max}}{\left|d_i^u(t)\right|_{\max}}\times100\%$, In the formula, $d_i^u(t)$ and $d_i^c(t)$ are seismic responses of i free degree of bridge without dampers and with dampers respectively. JZ_i is decreasing amplitude ratio of i free degree.

Table 1 shows the maximal seismic response of cable-stayed bridge under earthquake action.

Tab. 1 maximal seismic response of cable-stayed bridge

Ground motion	Seismic response	Dx21 /cm	Dx102 /cm	Dx20 /cm	**M32 /MN.m**	**M113 /MN.m**	**M20 /MN.m**	**Q32 /MN**	**Q113 /MN**	**N20 /MN**
Northridge uniform input	un	8.70	8.70	9.09	110.8	110.8	0.00	4.79	4.79	0.27
	Semi	4.17	4.17	3.54	110.8	110.8	0.00	4.82	4.82	0.26
	JZ_i	52%	52%	61%	0%	0%	0%	-1%	-1%	4%
	P-on	3.62	3.62	2.85	112.7	112.7	0.00	4.82	4.82	0.27
	JZ_i	58%	58%	69%	-2%	-2%	0%	-1%	-1%	0%
Northridge Traveling wave input	un	8.04	8.57	8.26	124.0	109.6	3.63	4.95	4.90	1.40
	Semi	3.30	3.59	3.10	121.0	110.4	3.61	4.93	4.89	1.43
	JZ_i	59%	58%	62%	2%	-1%	0%	0%	0%	-2%
	P-on	2.80	3.03	2.04	118.6	113.2	3.65	4.87	4.89	1.61
	JZ_i	65%	65%	75%	4%	-3%	-1%	2%	0%	-15%
Duzce uniform input	un	102.0	102.0	94.80	549.9	549.9	0.00	9.87	9.87	2.44
	Semi	42.41	42.41	38.63	308.3	308.3	0.00	9.76	9.76	2.52
	JZ_i	58%	58%	59%	44%	44%	0%	1%	1%	-3%
	P-on	36.30	36.30	29.81	308.9	308.9	0.00	9.54	9.54	2.62
	JZ_i	64%	64%	69%	44%	44%	0%	3%	3%	-7%
Duzce Traveling wave input	un	91.41	83.00	85.20	381.7	471.8	29.23	9.08	9.61	3.62
	Semi	46.56	53.50	42.27	295.7	289.8	28.59	9.16	9.78	3.40
	JZ_i	49%	36%	50%	23%	39%	2%	-1%	-2%	6%
	P-on	25.54	36.18	24.36	263.9	224.4	28.60	9.50	9.71	5.95
	JZ_i	72%	56%	71%	31%	52%	2%	-5%	-1%	-65%

From the table 1 it is can be seen as following:

(1) Semi-active and passive control can get good vibration-suppressed effectiveness for most of seismic responses of cable-stayed bridge, but vibration-suppressed effectiveness of some axial force of beam is negative. Seismic mitigation devices make the axial force larger.

(2) Although the peak accelerations of the two ground motions are the same, but the actions of the two ground motion on seismic response of cable-stayed bridge are different evidently. Seismic response under ground motion of Duzce is much greater than that under ground motion of Northridge. This is related to the frequency components of the two ground motions, in which Duzce ground motion has more long periods than Northridge ground motion.

(3) Vibration-suppressed effectiveness under the 2 ground motions are evidently different for seismic responses of controlled bridge, especially vibration-suppressed effectiveness of internal force of pier bottom are different evidently. This shows that the two control approaches of semi-active control and passive control are sensitive to ground motions. Vibration-suppressed effectiveness is related to ground motions nearly.

(4) The bridge is a symmetrical structure along middle span with damper set symmetrically.

Ground motion input is antisymmetric action for uniform ground motion input. Then moment is zero at the location of middle span. When seismic input is traveling wave input, ground motion input is no longer antisymmetric action. This moment is no longer zero. This shows traveling wave effect is disadvantage to beam of cable-stayed bridge.

(5) Traveling wave effect can make longitudinal displacement of tower and beam less, and make most seismic responses less at bottom of tower. This shows traveling wave effect is advantage to the tower.

(6) Influence of traveling wave effect on vibration-suppressed effectiveness of the two controls of semi-active control and passive control changes with different seismic responses. For the most seismic responses, traveling wave effect can give a little influence to the vibration-suppressed effectiveness with no obvious bad control effectiveness.

(7) Under the same ground motion input, vibration-suppressed effectiveness of passive control is better than that of semi-active control for most of seismic responses. But vibration-suppressed effectiveness of axial force N20 is not like this. Semi-active control and passive control can all makes axial force greater, but the amplifying effect of passive control is much greater than that of semi-active control. This shows that semi-active control is more advantage than passive control for the vibration-suppressed effectiveness of total seismic responses of bridge.

6 CONCLUSIONS

In this paper, influence of traveling wave effect on seismic semi-active control and passive control for long-span floating cable-stayed bridge is analyzed and the vibration-suppressed effectiveness is discussed with the three dimensional finite element model. Conclusion can be got as following:

(1) Seismic semi-active control and passive control can make most seismic responses of cable-stayed bridge less, but can make some seismic responses more including axial force of beam. So the parameters of cable-stayed bridge must be carefully analyzed when control devices are set on bridge.

(2) Ground motion inputs with different frequencies can severely influence seismic responses of cable-stayed bridge and vibration-suppressed effectiveness of semi-active control and passive control. Semi-active control is better than passive control with most damping force all along for vibration-suppressed effectiveness of the integer seismic responses of the cable-stayed bridge.

(3) Traveling wave effect can make longitudinal displacement of tower and beam less, most internal force at bottom of tower less and internal force of beam larger. Traveling wave effect can influence badly on beam of the cable-stayed bridge, but can influence advantageously on the piers.

(4) For most seismic responses of the cable-stayed bridge, traveling wave effect can bring a little bad influence on vibration-suppressed effectiveness of active control, semi-active control and passive control. There is no obvious phenomenon of control effect getting worse.

7 ACKNOWLEDGEMENTS

This article was written with support of National Science and Technology Supporting Plan of China (NO.2006BAC13B02) and National Natural Science Foundation of China (NO.50708100). The authors are grateful to the organizations.

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