Seismic Response of a Curved Bridge with Isolation Bearings

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SUMMARY
The use of horizontally curved bridges is very popular nowadays, especially to avoid a congested traffic and also to solve the limited space requirement in urban traffic conditions. The only problem with these types of bridges is the significant amount of torsion which makes it difficult for design.
From the study of damages caused by past earthquakes, it has been observed that the performance of bridges is generally governed by the performance of bearings and substructure. Selection of isolation bearings, especially in case of isolated curved bridges, is also a challenging task as the performance of a particular type of bearing is affected by age, temperature, scragging, velocity, travel, contamination and level of ground movement. In the present study, an attempt has been made to find out the most suitable isolation bearing for a horizontally curved bridge.

Keywords: Bridge, isolation bearing, seismic

1. INTRODUCTION

Horizontally curved bridges have become an important component in modern highway systems as the most viable option at complicated interchanges or river crossings where geometric restrictions and constraints of limited site space make extremely complicated the adoption of standard straight superstructures. Curved alignments offer, in addition, the benefits of aesthetically pleasing, traffic sight distance increase, as well as economically competitive construction costs with regard to straight bridges. Curved configurations may sustain severe seismic damage owing to rotation of the superstructure or displacement toward the outside of the curve line due to complex vibrations occurring during strong earthquake ground motions. It has been observed that in past earthquakes, most of the damages of the bridges occurred due to the failure of the bearings and substructure. So, bearings can play an important role in design of bridges. Considerable efforts have been made in the past two decades to develop improved seismic isolation design procedure for new bridges and comprehensive retrofit guidelines for existing bridges. Bearings may also be useful for curved bridges, but, still now, no effort has been taken to find out the most effective isolation system for curved bridges. This paper presents a numerical study of the seismic response of a continuous curved bridge with different types of isolation bearings. The effect of ground motion characteristics and level of ground excitation on the relative performance of different types of bearings have also been studied.

2. BEARING TYPES

A number of types of isolation bearings are now available. However, the present study is limited to a comparative assessment of the seismic performance of the three types of isolation bearings viz. High Damping Rubber (HDR) bearing, Lead Rubber Bearing (LRB) and Friction Pendulum System (FPS).

In HDR bearings (Grant et al., 2004), the additional damping is provided by modifying the rubber compound to develop hysteresis properties. The resulting hysteretic damping is generally represented

as equivalent viscous damping in the design. In the case of lead–rubber bearings (LRBs) (Abrahamson and Mitchell, 2003; Turkington et al., 1989), the rubber provides lateral flexibility to lengthen the period of the structure, and a lead core dissipates energy during cyclic movement due to earthquakes. The friction pendulum system (FPS) is a sliding-based seismic isolator (Dicleli, 2002; Ingham, 2003; Mokha et al., 1991; Wang et al., 1998) with a restoring mechanism. The FPS provides resistance to service load by friction. Once the coefficient of friction is overcome, an articulated slider moves over a spherical surface, which causes the supported mass to rise and provides the restoring force for the system. Friction between the articulated slider and the spherical surface generates damping. The Coulomb damping generated through sliding friction provides energy dissipation in the bearings.
The choice of bearing type in a particular situation is also influenced by the cost of the bearing. According to an evaluation (Drozdov et al., 2007) of FPS bearings, LRBs and bearings containing rubber with high damping capability, for the same levels of structural displacement, the FPS bearings were found to be the cheapest.

3. MODELLING AND ANALYSIS

For the study purpose, a continuous single-chamber box girder curved bridge has been considered. The total length of the curved bridge is 165 m with two end span of 20 m and five intermediate spans of 25 m. The radius of curvature of the bridge is 150 m. The cross-sectional area of the box-girder is 3.1 m^2. The longitudinal moment of inertia and transverse moment of inertia of the box-girder are 0.60 m^4 and 16.58 m^4, respectively. The pier has a solid circular section with corss-sectional area of 1.7671 m^2 and moment of inertia of 0.2485 m^4. The height of the pier is 11 m. The piers are resting on rocky strata.

The structure has been modelled using the SAP2000 non-linear software. The superstructure and the piers have been modelled using beam elements with mass lumped at discrete points. Since the piers are resting on rock, these have been modelled as fixed at the base. The abutments have been assumed to be rigid. The isolation bearings have been modelled as plastic link elements. For modelling purposes, bilnear force-deformation relationship with yield force, yield displacement, elastic stiffness, post-yield to elastic stiffness ratio have been considered for all the isolation bearings.

Two type of seismic loading (Figure 1) are considered in the study viz. (1)El centro (1940) (PGA: 0.313 g) and (2) Kobe (1995) (PGA: 0.821 g). The time history analysis of the bridge has been performed for the two loading conditions.

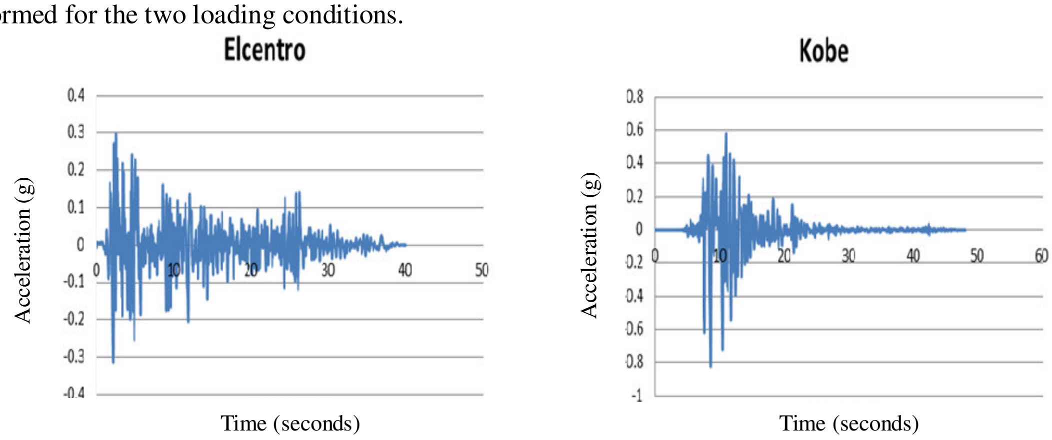

Figure 1. **Recorded Earthquake Ground Motions**

4. DESIGN OF ISOLATION BEARINGS

The design of the isolation bearings was carried out according to different criteria provided in various codes (AASHTO, 999; IRC, 1987) and the literature (Dolce et al., 2007; Priestley et al., 1996). Three parameters are important for the design of the isolation bearings viz. the period of the isolated structure, the damping of the isolation system and the level of ground movement. In the present study, the bearings have been designed for the selected earthquake ground motions and then the performance of different bearings has been compared.

5. PARAMETRIC STUDY

The response of the bridge with the HDR, LRB and FPS bearings has been studied. The natural period of the isolated structure and damping of the isolation device are the most important parameters affecting the response of the structure. These in turn depend on size and design of the isolation bearings. In the present paper, a sensitivity study of the bridge response for varying period and damping ratio was performed. For this purpose, the period range was considered as 1.5–2.5 s, and the range of damping was considered as 0.10 to 0.20. The ground motion histories have been applied independently in the longitudinal and transverse directions.

Tables 1-6 show the results of the sensitivity analysis of bridge response to bearing design parameters. The peak responses considered in the sensitivity analysis are the maximum deck displacement, the maximum base shear and the maximum base moment. It has been observed that the deck displacement is more sensitive w.r.to the change in time period than the change in damping. The effect of variation in damping is different for the different types of bearings. Some of the important observations from the tables are mentioned as follows:

- For El Centro ground motion in longitudinal and transverse directions with varying damping from 10% to 20%, Friction Pendulum System is more effective in reducing maximum deck displacement, High Damping Rubber bearing reduces the maximum base shear more effectively while Lead Rubber Bearing is more effective in reducing maximum base moment.
- For El Centro ground motion in longitudinal direction with varying time period from 1.5 sec to to 2.5sec, Friction Pendulum System is more effective in reducing maximum deck displacement and maximum base shear while lead Rubber Bearing is more effective in reducing maximum base moment.
- For El Centro ground motion in transverse direction with varying time period from 1.5 sec to to 2.5sec, Friction Pendulum System is more effective in reducing maximum deck displacement, High Damping Rubber bearing is more effective in reducing the maximum base shear and the maximum base moment.
- For Kobe ground motion in longitudinal direction with varying time period from 1.5 sec to 2.5 sec, Lead Rubber Bearing bearing is more effective in reducing maximum deck displacement, maximum base shear and maximum base moment.
- For Kobe ground motion in transverse direction with varying time period from 1.5 sec to to 2.5sec, High Damping Rubber bearing is more effective in reducing maximum deck displacement and the maximum base shear and Lead Rubber Bearing reduces maximum base moment more effectively.
- For Kobe ground motion in longitudinal direction with varying damping from 10% to 20%, Lead Rubber Bearing is more effective in reducing maximum deck displacement, maximum base shear and maimum base moment.
- For Kobe ground motion in transverse direction with varying damping from 10% to 20%, High Damping Rubber Bearing is more effective in reducing maximum deck displacement, maximum base shear and maximum base moment.

So, it can be stated that the overall performance of the FPS bearing is quite better in case of Elcentro ground motions while in case of Kobe ground motions, the performances of the HDR and LRB bearings are quite better.

Table 1: Response of Isolated Curved Bridge with Lead-Rubber Bearing for El Centro Ground Motion

Loading	Time Period (Second)	Damping (%)	Displ.$_x$ (m)	Displ.$_y$ (m)	S.F.$_x$ (KN)	S.F.$_y$ (KN)	B.M.$_x$ (KN-m)	B.M.$_y$ (KN-m)
El centro in Long. (X)-Direction	1.5	10	0.046	0.090	416.01	1095.52	8510.68	3742.70
		15	0.041	0.082	417.18	1113.50	8591.79	3753.22
		20	0.037	0.075	418.86	1182.62	9153.79	3757.42
	2	10	0.051	0.094	411.32	681.27	5308.88	3700.24
		15	0.048	0.092	412.95	710.47	5544.14	3714.63
		20	0.045	0.088	413.73	741.06	5800.39	3722.04
	2.5	10	0.057	0.107	416.32	527.00	4101.42	3750.17
		15	0.053	0.104	448.46	534.28	4397.94	3718.83
		20	0.051	0.101	465.67	547.27	4832.69	3745.11
El centro in Trans. (Y)-Direction	1.5	10	0.079	0.149	91.50	1663.90	12906.34	698.24
		15	0.071	0.136	93.34	1631.24	12940.24	744.16
		20	0.064	0.126	94.49	1675.81	13018.54	764.13
	2	10	0.080	0.147	98.44	1124.40	8697.90	918.65
		15	0.075	0.140	99.13	1125.59	8733.15	947.51
		20	0.071	0.136	101.98	1149.12	8922.40	968.78
	2.5	10	0.093	0.138	100.95	1058.77	8165.19	914.20
		15	0.092	0.134	101.46	1061.28	8197.94	918.83
		20	0.091	0.124	101.53	1078.66	8249.94	925.50

Table 2: Response of Isolated Curved Bridge with Friction Pendulum System for El Centro Ground Motion

Loading	Time Period (Second)	Damping (%)	Displ.$_x$ (m)	Displ.$_y$ (m)	S.F.$_x$ (KN)	S.F.$_y$ (KN)	B.M.$_x$ (KN-m)	B.M.$_y$ (KN-m)
El centro in Long. (X)-Direction	1.5	10	0.029	0.062	542.11	1196.16	8053.61	4878.81
		15	0.027	0.059	542.25	1254.71	11484.26	4880.04
		20	0.026	0.057	542.32	1328.81	12163.00	4880.69
	2	10	0.030	0.067	541.99	788.02	7213.64	4877.00
		15	0.029	0.066	542.12	812.10	7435.63	4878.89
		20	0.028	0.066	542.16	839.79	7698.13	4879.34
	2.5	10	0.038	0.069	541.91	544.99	4972.96	4874.82
		15	0.037	0.069	541.86	530.00	4851.97	4876.48
		20	0.036	0.068	542.02	556.29	5089.93	4877.98
El centro in Trans. (Y)-Direction	1.5	10	0.048	0.096	6.56	1995.76	18245.34	59.85
		15	0.046	0.093	6.63	2011.60	18384.84	56.86
		20	0.044	0.091	6.93	2040.38	18646.18	54.13
	2	10	0.054	0.102	7.05	1510.23	13785.67	64.38
		15	0.052	0.100	7.80	1513.86	13818.20	62.10
		20	0.050	0.097	8.35	1519.51	13901.13	61.00
	2.5	10	0.063	0.099	8.62	1167.53	10632.54	78.60
		15	0.062	0.097	8.88	1165.13	10609.33	77.27
		20	0.061	0.095	9.32	1163.13	10581.89	75.82

Table 3: Response of Isolated Curved Bridge with High Damping Rubber Bearing for El Centro Ground Motion

Loading	Time Period (Second)	Damping (%)	Displ.$_x$ (m)	Displ.$_y$ (m)	S.F.$_x$ (KN)	S.F.$_y$ (KN)	B.M.$_x$ (KN-m)	B.M.$_y$ (KN-m)
El centro in Long. (X)-Direction	1.5	10	0.049	0.096	542.15	1001.36	9170.72	4879.12
		15	0.045	0.090	542.21	1042.17	9548.05	4879.72
		20	0.044	0.090	542.21	1124.73	10308.20	4879.64
	2	10	0.049	0.098	541.67	558.752	5114.20	4874.76
		15	0.047	0.095	541.68	611.623	5863.35	4875.21
		20	0.047	0.093	541.76	678.707	6217.45	4875.60
	2.5	10	0.052	0.098	541.40	464.576	4240.93	4872.28
		15	0.049	0.096	541.44	472.776	4317.55	4872.64
		20	0.047	0.096	541.47	482.551	4408.88	4872.91
El centro in Trans. (Y)-Direction	1.5	10	0.080	0.155	10.09	1463.66	13493.68	100.46
		15	0.073	0.143	10.10	1465.04	13410.66	91.40
		20	0.069	0.137	10.53	1476.86	13516.48	86.96
	2	10	0.079	0.138	10.00	1008.08	10016.21	98.16
		15	0.073	0.135	10.09	1087.16	9793.51	94.13
		20	0.068	0.134	10.28	1098.69	9590.49	90.16
	2.5	10	0.088	0.130	9.55	986.45	8886.66	105.26
		15	0.085	0.126	9.57	994.10	8954.32	100.92
		20	0.082	0.124	9.68	1006.82	9068.98	97.33

Table 4: Response of Isolated Curved Bridge with Friction Pendulum System for Kobe Ground Motion

Loading	Time Period (Second)	Damping (%)	Displ.$_x$ (m)	Displ.$_y$ (m)	S.F.$_x$ (KN)	S.F.$_y$ (KN)	B.M.$_x$ (KN-m)	B.M.$_y$ (KN-m)
Kobe in Long. (X)-Direction	1.5	10	0.062	0.143	1023.02	2805.00	25549.01	9216.36
		15	0.061	0.142	1023.89	2806.80	25629.00	9218.35
		20	0.060	0.142	1024.22	2808.14	25748.48	9219.44
	2	10	0.088	0.152	1022.84	1704.96	15557.51	9210.11
		15	0.063	0.131	1023.06	1719.37	15840.31	9215.32
		20	0.063	0.119	1023.33	1735.58	16929.43	9215.55
	2.5	10	0.091	0.164	1019.28	1069.99	9835.09	9109.80
		15	0.090	0.162	1019.97	1075.52	9904.53	9110.99
		20	0.090	0.161	1022.57	1087.57	9942.68	9177.04
Kobe in Trans. (Y)-Direction	1.5	10	0.096	0.185	19.80	4317.32	42320.59	184.96
		15	0.095	0.180	19.81	4418.32	42368.58	185.06
		20	0.094	0.178	19.89	4419.62	40389.27	185.41
	2	10	0.112	0.231	17.15	2849.87	26028.31	156.40
		15	0.105	0.209	17.22	2896.33	26335.25	156.51
		20	0.096	0.205	17.32	2965.92	26986.30	157.94
	2.5	10	0.141	0.219	13.89	2178.34	19413.76	121.36
		15	0.141	0.210	13.97	2196.45	19706.32	122.13
		20	0.140	0.208	14.05	2230.60	19962.55	122.88

Table 5: Response of Isolated Curved Bridge with Lead Rubber Bearing for Kobe Ground Motion

Loading	Time Period (Second)	Damping (%)	Displ.$_x$ (m)	Displ.$_y$ (m)	S.F.$_x$ (KN)	S.F.$_y$ (KN)	B.M.$_x$ (KN-m)	B.M.$_y$ (KN-m)
Kobe in Long. (X)-Direction	1.5	10	0.031	0.074	312.01	899.36	6936.23	3236.70
		15	0.029	0.074	318.01	900.05	6950.01	3240.03
		20	0.028	0.072	322.33	921.26	6980.11	3259.45
	2	10	0.051	0.075	300.26	783.67	6123.22	3103.06
		15	0.049	0.074	309.56	800.33	6219.15	3119.16
		20	0.047	0.073	313.21	829.31	6397.17	3129.33
	2.5	10	0.056	0.076	295.13	717.11	5805.36	3012.81
		15	0.052	0.075	301.24	742.31	5916.23	3089.12
		20	0.050	0.074	309.46	783.28	6096.48	3119.35
Kobe in Trans. (Y)-Direction	1.5	10	0.061	0.115	71.53	1268.15	8967.34	496.34
		15	0.060	0.109	75.64	1279.49	9009.15	506.34
		20	0.059	0.100	81.64	1291.15	9081.15	522.34
	2	10	0.064	0.123	66.34	1240.12	8838.65	479.21
		15	0.063	0.119	69.15	1259.67	8892.34	487.55
		20	0.061	0.109	72.34	1271.25	8929.12	498.24
	2.5	10	0.067	0.144	65.78	1205.48	8809.10	466.22
		15	0.066	0.136	63.56	1225.67	8854.32	469.96
		20	0.065	0.125	60.22	1262.34	8861.23	472.75

Table 6: Response of Isolated Curved Bridge with High Damping Rubber Bearing for Kobe Ground Motion

Loading	Time Period (Second)	Damping (%)	Displ.$_x$ (m)	Displ.$_y$ (m)	S.F.$_x$ (KN)	S.F.$_y$ (KN)	B.M.$_x$ (KN-m)	B.M.$_y$ (KN-m)
Kobe in Long. (X)-Direction	1.5	10	0.039	0.088	485.32	869.36	6954.47	5435.48
		15	0.038	0.087	501.32	885.34	7012.65	5516.75
		20	0.037	0.086	529.64	906.75	7215.78	5619.85
	2	10	0.043	0.089	467.48	832.56	6220.18	5200.68
		15	0.042	0.088	489.45	802.35	6381.22	4897.42
		20	0.041	0.087	502.78	788.70	6566.48	4766.35
	2.5	10	0.045	0.091	432.35	762.38	6025.47	5019.45
		15	0.043	0.090	467.12	779.34	6222.41	4727.22
		20	0.042	0.088	488.12	784.44	6434.88	4685.45
Kobe in Trans. (Y)-Direction	1.5	10	0.065	0.098	18.12	1102.75	9635.34	103.14
		15	0.064	0.097	20.14	1162.14	9852.21	110.32
		20	0.063	0.095	22.47	1198.36	9969.33	116.75
	2	10	0.068	0.112	16.33	1088.22	9554.15	98.15
		15	0.067	0.099	18.15	1153.36	9545.33	100.36
		20	0.066	0.097	20.43	1178.48	9781.64	105.89
	2.5	10	0.071	0.120	15.36	996.65	9306.66	95.23
		15	0.069	0.111	16.22	1004.13	9456.32	96.17
		20	0.067	0.101	17.45	1018.29	9696.18	97.23

6. CONCLUSIONS

The effect of type of isolation bearings on the seismic response of a continuous curved bridge has been studied. It has been observed that the LRB system, HDR system and FPS have similar good performance, resulting in lower deck displacements and pier forces, for the ground motions considered in the study. It has been observed that in case of ground motions close to active fault (Kobe) the performances of the elastomeric based systems (HDR and LRB) are better in comparison to friction based systems (FPS). Otherwise, FPS is quite effective isolation system among the others. However, any of these systems can be used depending on the availability of skill and cost considerations for local conditions.

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