A COMPARATIVE STUDY OF THERMAL AND SEISMIC BEHAVIOUR OF A BRIDGE WITH TRADITIONAL AND ISOLATION BEARINGS

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ABSTRACT :

Design of bearings for earthquake displacements and resistance is important for safety of bridges. Traditionally, bearings have been designed for movements generated due to temperature, shrinkage and creep. However, the bearings have to play a vital role during earthquake also. Most of the failures during past earthquakes have been reported due to failure of bearings and substructure. Therefore, it is an important task to select suitable bearings for both thermal and seismic conditions. This paper examines the thermal and seismic response of (i) Traditional Roller-Rocker bearings, and (ii) Isolation Bearings viz. Elstomeric Bearings with and without Dampers, Friction Pendulum Systems (FPS) for a three-span continuous bridge. The effect of arrangement of the bearings for the bridge has also been examined. The range of the time period for the different arrangements of the bearings for the continuous bridge has also been obtained. A three dimensional model of the bridge has been developed. A site specific design response spectrum with a set of five acceleration time histories have been used for study of the seismic response. It has been found that isolation bearings have much better thermal and seismic performance than traditional rocker and roller bearings. The performances of FPS systems are quite satisfactory. However, in respect of restoring coefficient, the performances of the Viscous Damper alongwith Elastomeric Bearings are better than the FPS systems.

KEYWORDS: Bridge, Bearing, Thermal, Seismic, Isolation

1. INTRODUCTION

There are many examples of collapse of bridges caused by relative movement of spans in the longitudinal direction due to failure of bearings. The traditional rocker and roller bearings have limited movement capacity and transmit considerable earthquake forces to the substructure and result in failure of the bridges due to failure of piers or bearing. The development of modern isolation bearings has caused revolutionary change in the concepts of bearing design. These bearings are designed to perform an additional function by isolating the superstructure from the vibrations transmitted by the substructure. But this may result in considerably large displacement of superstructure. Therefore, it is an important task to select the suitable bearing, which transmits lesser forces to the substructure and, at the same time, does not result in large displacement of the superstructure. This paper presents a comparative study of thermal and seismic response of a three span continuous bridge with traditional and isolation bearings. A three dimensional model of the bridge has been developed with nonlinear modeling of the bearings. For thermal loading, a temperature difference of 25^{o}C and the coefficient of thermal expansion of $11.7\times10^{-6}/^{o}$C have been considered. In case of seismic loading, a site specific design response spectrum and a set of five acceleration time histories have been used. Six different arrangements representing different possible combinations of bearings have been considered on piers and abutments. The response of the continuous bridge has been studied for (i) Roller-Rocker bearings, and (ii) Isolation Bearings viz. Elastomeric Bearing with and without Viscous Dampers, Friction Pendulum Systems (FPS).

2. BRIDGE CONSIDERED FOR THE STUDY

An existing three span railway bridge, situated in Northern India, has been considered. The site of the bridge falls in Seismic Zone IV of Indian Seismic Zoning (IS: 1893-2002, Part 1). It is a continuous prestressed concrete box girder bridge. The bridge has a total length of 192 m with the main span of 80 m and two end spans of 56 m, each (Figure 1). The cross-sectional details of box girder are shown in Figure 2. The height of the piers is 36.355 m. The pier section is hollow circular with an external diameter of 6.5 m and thickness of 0.5 m. The piers are resting on rocky strata.

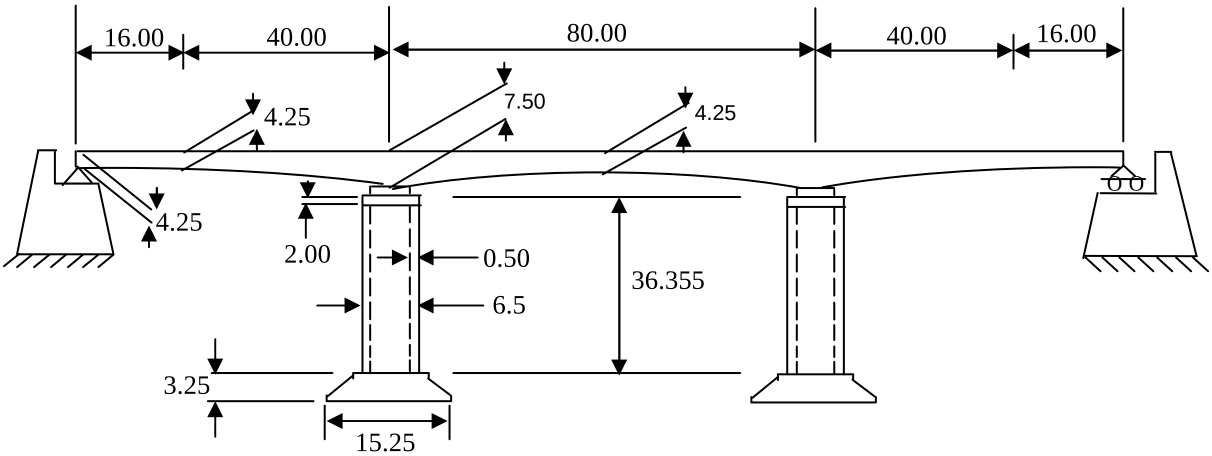


Figure 1 Three span continuous bridge. (dimensions are shown in meter)

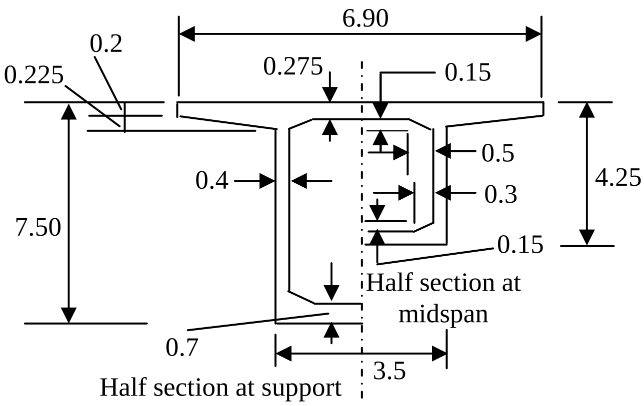


Figure 2 Box-girder section of the continuous bridge (dimensions are shown in meter)

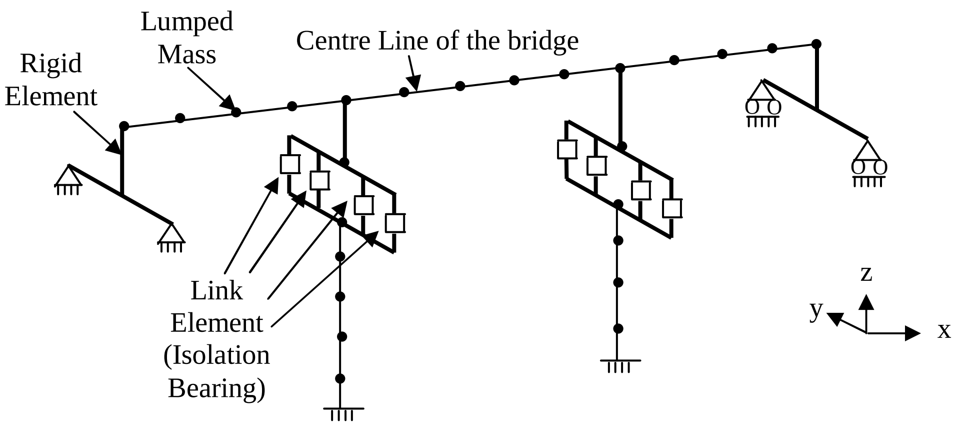


Figure 3 3-D mathematical model of the continuous bridge

3. ANALYTICAL MODELLING

The structure has been modeled (Figure 3) using the software SAP2000 Nonlinear. The superstructure and the piers have been modeled using beam elements with mass lumped at discrete points. Since the piers are resting on rock, these are modeled as fixed at base. The abutments have been assumed to be rigid. The Isolation Bearings have been modeled as link elements while the Roller and Rocker Bearings have been modeled as appropriate boundary conditions. To model the spatial placement of bearings across the section, horizontal cross rigid links as shown in Figure 3 have been used.

4. BEARING ARRANGEMENTS CONSIDERED

In the present study, six different arrangements (Figure 4) representing different possible combinations of Bearings have been considered.

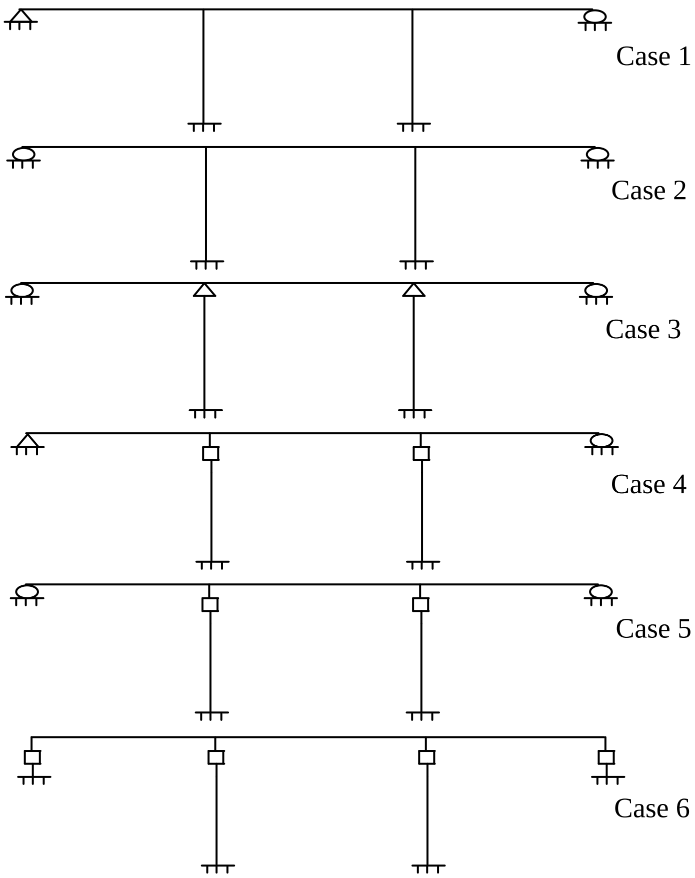


Figure 4 Different bearing arrangements considered for the study

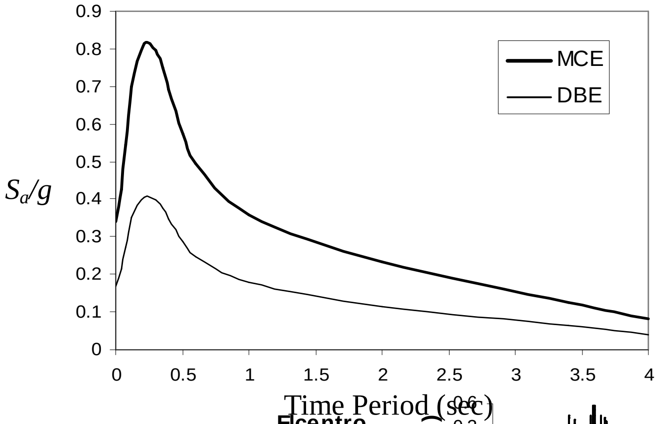
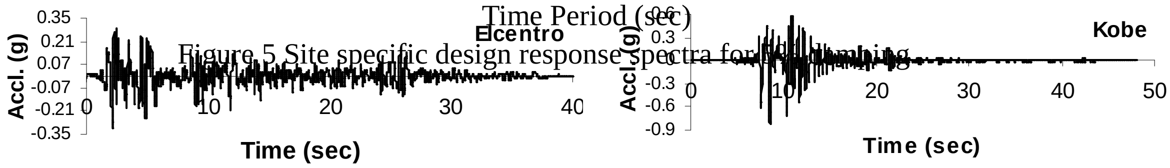


Figure 5 Site specific design response spectra for 5% damping



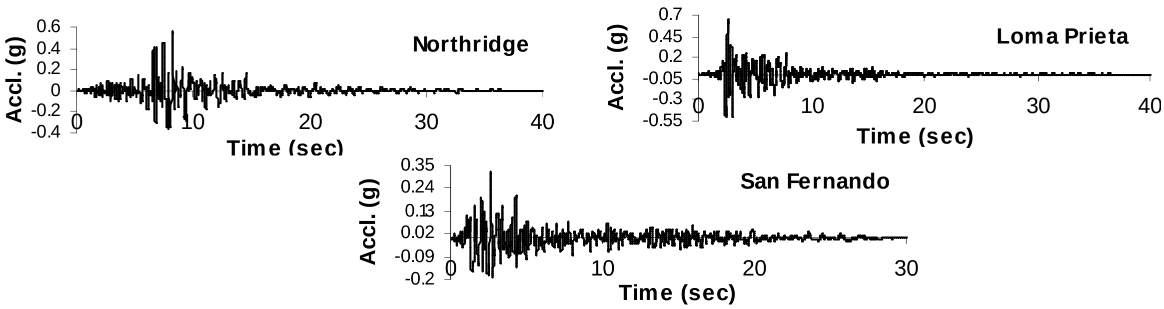


Figure 6 Ground motion time histories considered for the study

7. SEISMIC LOADING

Site specific response spectra are available (Figure 5) for the bridge site for the Design Basis Earthquake (DBE) and the Maximum Considered Earthquake (MCE). In case of seismic loading, five ground acceleration time histories (Figure 6), recorded for different earthquakes, world over, for different source and site conditions have been scaled in frequency domain, preserving their phase information (Kumar 2004), to make them compatible with the design response spectra.

8. DETERMINATION OF THE RANGE OF THE ISOLATION TIME PERIOD

In Fourth and Fifth Bearing Arrangements (Figure 4), the Isolation Bearings have been used on piers while Traditional Rocker/Roller Bearings on abutments. In case of a Rocker Bearing used on abutment (Fourth Bearing Arrangement), the structure becomes very stiff in the longitudinal direction and time period in longitudinal direction cannot be much elongated by providing Isolation Bearings on the piers. However, in case of Roller Bearings on both the abutments (Fifth Bearing Arrangement), the time period in longitudinal direction can be elongated to any extent by reducing the stiffness at supports on piers using isolation. However, in transverse direction the girder is restrained against translation at the abutment ends in both the cases (Fourth and Fifth Bearing Arrangements). This restricts the range to which the time period in the transverse direction can be elongated by providing Isolation Bearings on the piers.

The stiffness of the Isolators is equal in both the directions. Therefore in both the cases, the design of Isolation Bearings will be governed by the transverse direction. To determine the maximum time period which can be achieved in transverse direction, a simple approximate formulation can be obtained using Principle of Superposition and considering the equivalent lumped mass at each Bearing support. The deflection, δ_1 of girder at pier top, due to uniform transverse acceleration (say equal to 1g) and assuming zero stiffness of Isolation Bearings at the top of the piers, can be obtained by linear static analysis. Similarly, the deflection, δ_2 of the end supported girder subjected to unit transverse load at the Bearing locations can also be evaluated. The final deflection δ of the girder in the presence of Bearing having effective stiffness K_{eff} can be written as

$$\delta = \delta_1 - \delta_2 K_{eff} \delta \tag{7.1}$$

The final deflection due to uniform lateral acceleration equal to 1g can also be expressed in terms of the target time period, T_{Target}, as

$$\delta = \frac{g}{4\pi^2} \times (T_{Target})^2 \tag{7.2}$$

Using the above two equations the effective stiffness corresponding to a target time period can be estimated. It is obvious that the maximum time period will correspond to zero effective stiffness of the Isolation Bearing, which is equal to

$$T_{\max} = 2\pi \sqrt{\frac{\delta_1}{g}} \tag{7.3}$$

Table 8.1 Time period of the bridge for various cases

Bearing Arrangement	T_{Target}	$K_{per\ Isolator}$	$T_{Act,\ Trans.}$	$T_{Act,\ Long.}$
	(sec)	(kN/m)	(sec)	(sec)
4	1.5	1232	1.47	0.217
4	1.6	787	1.63	0.22
4	1.8	-859	-	-
4	2	-1762	-	-
5	1.5	2378	1.62	2.10
5	1.75	1459	1.82	2.78
5	2	863	2.04	3.5
5	2.3	387	2.306	5
5	2.5	161	2.41	7
6	2	1927	2.2	1.9
6	2.5	1233	2.67	2.35
6	3	856	3.14	2.8

It can be seen from Table 8.1 that the maximum possible isolation time period of the bridge along the transverse direction in the Fourth Bearing Arrangement is about 1.6 sec. A higher target time period demands negative stiffness of the Bearing which is not physically possible. Further, the longitudinal isolation time period in Fifth Bearing Arrangements increases to impracticable range for transverse isolation beyond a certain range (2 sec). In Sixth Bearing Arrangement, the Isolators are placed at the abutment supports as well as over the piers. The effective mass vibrating in both the directions is equal to the total mass of the superstructure. So, the time period of the bridge will be approximately same in both the directions. In this case, theoretically, the isolation is possible upto any extent, however, it is impractical to have time periods beyond 3 sec, as this will result in excessive deflections.

9. DESIGN OF ISOLATION BEARINGS

The design of the Isolation Bearings has been done according to different criteria provided in various codes (AASHTO 1999; FEMA-356; IRC: 83, Part-II 1987) and literature. Three parameters are important for the design of the Isolation Bearings, i.e. time period of the isolated structure, damping ratio of the Isolation System and the level of shaking. In the present study, the Bearings have been designed for MCE and the performance has been studied for MCE, as well as, for DBE.

Another important characteristic of the base Isolation Systems is the lateral restoring effect. A Restoring Coefficient has been defined as the ratio of the difference of the restoring force at design displacement and 50% of the design displacement, to the seismic weight. Restoring coefficient represents the reliability of the Isolation System in limiting the displacements under unforeseen conditions during the actual earthquake motion to which the structure may be subjected. As per FEMA and UBC, this restoring coefficient should be greater than 0.025, otherwise the Isolation System has to be designed to accommodate 3 times the design displacements. In the present study, the restoring coefficients for all the Isolation Bearings have been determined and the effectiveness of the Isolators in restricting the lateral displacements has been examined.

Tables 9.1 show the design and response parameters of different types of Isolation Bearings, respectively, designed for MCE loading condition.

10. THERMAL RESPONSE

Table 10.1 shows the thermal response of the bridge for all the Bearing Arrangements studied. The thermal load applied corresponds to a temperature difference of 25^{o}C and the coefficient of thermal expansion has been considered as $11.7\times10^{-6}/^{o}$C.

10.1. Traditional Bearings

From Table 10.1, it can be observed that the maximum deck displacement of the bridge occurs in case of the First Bearing Arrangement. This is because in the First Bearing Arrangement the movement of the bridge is restricted at one abutment and the whole of the displacement takes place at the other abutment, whereas in the other cases, the bridge is free to move in the longitudinal direction at both the abutments. Consequently, force transmitted to the piers is also maximum in First Bearing Arrangement. The force transmitted to the pier is minimum in the Third Bearing Arrangement, as the bridge deck is free to translate at both the ends and the piers are not monolithically connected with the superstructure.

10.2. Isolation Bearings

From Table 10.1, it can be observed that the deck displacement of the bridge with the different types of the Isolation Bearings for a particular Bearing Arrangement remains the same. This is because the stiffness of the Isolation Bearings is much smaller compared to the axial stiffness of the girder. It has also been found that the deck displacement of the bridge in the Fourth Bearing Arrangement is twice as compared to Fifth and Sixth Bearing Arrangements. This happens due to the restriction of movement of the bridge along the longitudinal direction by the Rocker Bearings at one abutment, in the Fourth Bearing Arrangement.

It can also be seen that the forces transmitted to the piers and abutments are very small in all the Bearing Arrangements with Isolation Bearings. This is an added advantage of using Isolation Bearings. The force transmitted by different types of Bearings is different and the EL and ELDM result in the minimum force. The thermal movement takes place at a slow rate and therefore it is not affected by presence of Dampers. Therefore, ELDM and EL result in essentially the same force transmitted to the piers and abutments. However, this force is much smaller than the seismic forces, to affect the choice of the Bearings, for the selected moderate span bridge. In case of longer span bridges, this may be significant and can affect the choice of Bearings.

Table 9.1 Properties of isolation systems designed for MCE loading condition

System	Characteristic Strength	Isolated Period	Effective Damping	Bearing Displacement	Initial Stiffness	Post-yield Stiffness	Yield Force	Restoring Coefficient
	(kN)	(sec)	(%)	(m)	(kN/m)	(kN/m)	(kN)	
EL	-	2.0	2	0.218	1927	-	-	0.075
EL	-	2.5	2	0.299	1233	-	-	0.065
EL	-	3.0	2	0.349	856	-	-	0.053
ELDM	-	2.0	10	0.160	1927	-	-	0.075
ELDM	-	2.0	20	0.132	1927	-	-	0.075
ELDM	-	2.0	30	0.112	1927	-	-	0.075
ELDM	-	2.5	10	0.207	1233	-	-	0.065
ELDM	-	2.5	20	0.166	1233	-	-	0.065
ELDM	-	2.5	30	0.141	1233	-	-	0.065
ELDM	-	3.0	10	0.237	856	-	-	0.053
ELDM	-	3.0	20	0.190	856	-	-	0.053
ELDM	-	3.0	30	0.161	856	-	-	0.053
FPS	0.018	2.0	10	0.160	-	3248	98	0.046
FPS	0.035	2.0	20	0.135	-	2638	199	0.032
FPS	0.038	2.0	30	0.115	-	2021	213	0.021
FPS	0.044	2.0	40	0.100	-	1388	249	0.012
FPS	0.015	2.5	10	0.210	-	2078	82	0.039
FPS	0.024	2.5	20	0.175	-	1688	138	0.026
FPS	0.032	2.5	30	0.150	-	1294	178	0.017
FPS	0.037	2.5	40	0.130	-	889	207	0.010
FPS	0.013	3.0	10	0.270	-	1443	74	0.035
FPS	0.022	3.0	20	0.225	-	1172	123	0.023
FPS	0.030	3.0	30	0.190	-	898	156	0.015
FPS	0.032	3.0	40	0.165	-	617	183	0.010

Table 10.1 Thermal response of the bridge

Bearing Arrangement	Bearing Types	Deck Displacement	Force Transmitted to the pier	Abutment Shear Force
		(m)	(kN)	(kN)
1	Roller-Rocker	0.053	5093	6661
2	Roller	0.028	1816	0
3	Roller-Rocker	0.028	444	0
4	EL	0.056	76	340
4	FPS	0.056	539	1328
4	ELDM	0.028	76	340
5	EL	0.028	102	0
5	FPS	0.028	599	0
5	ELDM	0.028	102	0
6	EL	0.028	120	140
6	FPS	0.028	504	366
6	ELDM	0.028	120	140

11. SEISMIC RESPONSE

Tables 11.1-11.2 show the seismic response of the bridge with different types of Bearings, for design spectrum compatible (scaled) ground motions. In this case, the average of peak response for the five time histories has been considered.

11.1. Traditional Bearings

From Table 11.1 it can be observed that the time period of the bridge along longitudinal direction in the Second and Third Bearing Arrangements is higher than that in First Bearing Arrangement. This is because the bridge is supported on Roller Bearings at both the abutments, in the Second and Third Bearing Arrangements, which makes it flexible along the longitudinal direction. It can also be observed that the maximum deck displacement of the bridge occurs in Third Bearing Arrangement, because the bridge is most flexible in this case. When the bridge superstructure is constrained with Rocker Bearings at one of the abutments (First Bearing Arrangement), the maximum displacement of the bridge in the longitudinal direction is reduced to negligible amount.

The force transmitted to the pier in the First Bearing Arrangement is lesser by 78% and 68%, as compared to the Second and Third Bearing Arrangements, respectively. The reduced force transmitted to the pier is associated with high reaction force at the abutment, on which the displacement constraint is provided. Normally, the abutments are intrinsically much stronger than the piers. They can therefore resist much higher forces than the piers. Special attention is to be paid to the capacity of the Rocker Bearings and their anchorages, as these would become critical in seismic design.

Table 11.2 shows that the time period of the bridge in transverse direction is almost same for all the arrangements of Traditional Bearings. This is because the Traditional Bearings result in rigid connection between the superstructure and substructure, in transverse direction. The maximum deck displacement, maximum force transmitted to the pier and maximum abutment shear force of the bridge are almost same for all the non-isolated cases considered.

11.2. Isolation Bearings

It can be observed from Tables 11.1 and 11.2 that the deck displacement and force transmitted to the piers and abutments are quite different, in case of different Isolation Bearings. Elastomeric Bearing has resulted in higher deck displacement, as well as, higher force transmitted to the piers and abutments, in all the Bearing Arrangements considered in the study. This happens because the Elastomeric Bearings behave linearly and there is very little energy dissipationUse of Dampers in the ELDM system has resulted in reduced deck displacements but higher forces in the piers.

Table 11.1 Seismic response of the bridge along longitudinal direction for scaled earthquake ground motions

Bearing Arrangement	Bearing Types	Time Period	Deck Displacement		Force Transmitted to pier		Abutment Shear Force		Energy Dissipated		Permanent Displacement	
			DBE	MCE	DBE	MCE	DBE	MCE	DBE	MCE	DBE	MCE
		(sec)	(m)	(m)	(kN)	(kN)	(kN)	(kN)	(kN-m)	(kN-m)	(m)	(m)
1	Roller-Rocker	0.22	0.006	0.013	883	1766	14122	28243	0	0	0	0
2	Roller	0.82	0.036	0.072	4039	8077	0	0	0	0	0	0
3	Roller-Rocker	1.47	0.076	0.153	2735	5471	0	0	0	0	0	0
4	EL	0.23	0.006	0.012	380	580	13017	26034	0	0	0	0
4	FPS	0.23	0.003	0.006	222	480	10195	20187	2	28	0	0
4	ELDM	0.23	0.003	0.006	346	500	9702	19345	31	125	0	0
5	EL	3.5	0.164	0.328	1096	2100	0	0	0	0	0	0
5	FPS	3.5	0.045	0.167	744	1312	0	0	544	2048	0	0
5	ELDM	3.5	0.117	0.233	1048	2088	0	0	385	1540	0	0
6	EL	2.5	0.129	0.259	1216	2435	639	1277	0	0	0	0
6	FPS	2.5	0.032	0.099	840	1182	430	612	612	2283	0	0
6	ELDM	2.5	0.068	0.136	992	1995	391	782	547	2188	0	0

Table 11.2 Seismic response of the bridge along transverse direction for scaled earthquake ground motions

Bearing Arrangement	Bearing Types	Time Period	Deck Displacement		Force Transmitted to pier		Abutment Shear Force		Energy Dissipated		Permanent Displacement	
			DBE	MCE	DBE	MCE	DBE	MCE	DBE	MCE	DBE	MCE
		(sec)	(m)	(m)	(kN)	(kN)	(kN)	(kN)	(kN-m)	(kN-m)	(m)	(m)
1	Roller-Rocker	0.99	0.062	0.124	2901	5802	1265	2530	0	0	0	0
2	Roller	1.08	0.069	0.137	2762	5523	1057	2115	0	0	0	0
3	Roller-Rocker	1.08	0.069	0.137	2762	5523	1057	2115	0	0	0	0
4	EL	1.6	0.112	0.223	980	1660	2802	5604	0	0	0	0
4	FPS	1.6	0.053	0.127	816	1384	1515	3505	280	1139	0	0
4	ELDM	1.6	0.070	0.139	1008	1880	1877	3753	216	865	0	0
5	EL	2	0.161	0.322	848	1688	0	0	0	0	0	0
5	FPS	2	0.061	0.169	464	1136	0	0	485	2005	0	0
5	ELDM	2	0.121	0.238	904	1800	0	0	423	1693	0	0
6	EL	2.5	0.179	0.357	1472	2952	646	1291	0	0	0	0
6	FPS	2.5	0.054	0.157	896	1433	386	647	574	2473	0	0
6	ELDM	2.5	0.099	0.199	1264	2523	388	776	622	2488	0	0

FPS systems have shown comparable and good seismic performance for the various ground motions considered. These result in lower deck displacements and pier forces, as compared to other systems.
Table 9.1 show the restoring coefficient for different types of Isolation Systems. In case of FPS systems the restoring coefficient falls below the limit of 0.025 for longer periods and higher damping. From this point of view, ELDM represents a more reliable system, as the low damping rubber used in the system, does not yield and has high stiffness right up to the design displacement.

12. CONCLUSIONS

The performance of different types and arrangements of Traditional Rocker-Roller Bearings and Isolation Bearings has been studied under thermal and seismic loading conditions. It has been observed that Isolation Bearings have distinct advantage over Traditional Bearings, both against thermal and seismic loading. Providing isolation bearings at all the piers and abutments results in a performance better than that of a combination of Traditional and Isolation Bearings. The performances of the FPS systems have been satisfactory as these resulted in lower deck displacements, and pier and abutment forces, for the ground motions considered in the study. However, these bearings have shown poor restoring effect at longer time periods and higher damping. Use of Viscous Dampers alongwith Elastomeric Bearings has resulted in reduced deck displacements but higher forces in piers. However, in respect of restoring coefficient, this system is still quite better than the FPS system.

REFERENCES

IS: 1893-Part 1 (2002). Criteria for Earthquake Resistant Design of Structures-General Provisions and Buildings, Bureau of Indian Standards, New Delhi.
Kumar, A. (2004). Software for generation of spectrum compatible time history. *Proc. 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, August, paper no. 2096.
SAP2000 (2006). Integrated Finite Element Analysis and Design of Structures, Computers and Structures Inc., Berkeley, Calif.
American Association of State Highway and Transportation Officials (AASHTO). (1991). Guide specifications for seismic isolation design, Washington, D. C.
Federal Emergency Management Agency. (2000). Prestandard and commentary for the seismic rehabilitation of buildings.FEMA-356. Washington, D.C.
IRC: 83 (Part II) .(1987). Standard specifications and code of practice for road bridges- section IX- bearings (part II): elastomeric bearings. Indian Road Congress, New Delhi.