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Comparative Study on the Seismic Performance of Reinforced Concrete and Suspension Bridges with and without Base Isolation Systems

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Abstract

This paper investigates the performance of reinforced concrete (RC) and suspension bridges equipped with isolation bearings under seismic excitations. Three different isolation bearings such as Lead Rubber Bearing (LRB), High Damping Rubber Bearing (HDRB) and Friction Pendulum System (FPS) are considered in this study. The bridges were modelled and analysed using SAP 2000 software. In order to study the performance of isolation bearings in mitigating seismic effects on the bridges, non linear time history analysis was performed on the bridges with four different ground motions namely Landers, Maule, Northridge and Kobe. The seismic response of the isolated bridges were compared with that of the bridges without isolation system. The response parameters considered for this study are the base shear, acceleration of the bridge deck, displacement of the bridge deck, axial force on cables and the pier displacement. The comparative analysis confirmed that the base isolation system was an effective tool in reducing the accelerationof the bridge deck, axial force on the cables and also the base shear force.

Keywords : Seismic Isolation Bearings – LRB, HDRB and FPS, Time History Analysis, Seismic Response.

I. INTRODUCTION

An earthquake is the shaking of the surface of the earth resulting from a sudden release of energy in the earth's lithosphere. The protection of structures against seismic disturbances is a major topic of research for many years. Rapid movement of the faults within the Earth’s crust produce dynamic forces that causes earthquakes. The movement of faults release energy in the form of seismic waves. These seismic waves reach the foundation of the structure that results in the movement of the structure. These complex movements results in horizontal and vertical vibrations in structures called as responses such as displacements, velocities and accelerations. Retrofitting a component of bridge may overstress some other components and result in additional retrofitting cost. Mobilization and traffic control during substructure retrofitting over an extended period of time constitutes an additional hidden cost that need to be considered [7].

Conventional seismic retrofitting methods [4] may be used to mitigate the risk that currently exists for seismically vulnerable bridges. Some of these methods include; replacing old steel bearings with modern conventional bearings such as elastomeric, pot or spherical bearings, widening the pier cap and abutment seat to accommodate seismic lateral movements of the superstructure, strengthening and enhancing the ductility capacity of the columns using concrete and steel jackets, advanced composite fibre reinforced polymer or prestressed wire wrapping, increasing the size of the footings and the number of piles and providing dead man anchors to improve the lateral resistance of the footings. However, most of these retrofitting methods are expensive and difficult to implement. Thus designing the structures to resist seismic forces is of vital importance.

The seismic response of bridges depends to a great extent on how the bridge deck is connected to the tower and the piers. Rigid connections limit the deck horizontal displacements under earthquake action but unavoidably increase the transmitted forces between the superstructure and the sub-structure. There is a general agreement in the convenience of permitting certain relative movement of the deck at the pier and tower locations, to reduce the internal forces at the base of these elements but, due to the low inherent damping, important horizontal displacements are to be expected in that location. This behaviour suggests seismic control techniques, i.e. passive, active or semi-active control, as possible alternatives to improve the performance of the bridges under strong earthquake ground motions.

In a mitigation context, two main objectives are pursued: (i) to increase the structure's fundamental period and therefore reduce the spectral acceleration demand levels and (ii) to enhance the energy dissipation capabilities of the bridge and thereby, increasing the damping. In this regard, two approaches may be adopted: (i) introduction of dampers for energy dissipation (ii) isolating totally or partially the bridge deck from the substructure, leading to minimum member forces but maximum deck horizontal displacements. Thus, an economical and innovative method for mitigating the seismic forces on the bridges is by replacing the already vulnerable existing bearings by seismic isolation bearings thereby eliminating the need for costly retrofitting.

Seismically isolated structures have shown reduced damage and superior seismic performance during extreme earthquake events. The advantages of protecting structures in seismic regions using isolation bearings have been recognized all over the world. Especially for bridges, seismic isolation bearings are the preferred choice over other seismic protection systems for seismic upgradation of existing structures as well as for new constructions. One of the main objectives of using isolation bearings is to modify the fundamental period of the structure away from the predominant earthquake period thus reducing the seismic demand on the structure.

Damage or residual displacement of the superstructure and bearings easily happened for simply supported girder bridge and continuous girder bridge in earthquakes. In Loma Prieta earthquake, a span of the San Francisco Oakland Bay Bridge collapsed [5]. In Wenchuan earthquake, the centre curb of Miaoziping Bridge crashed due to the collision of adjacent girder [6]. In Chile earthquake, one girder moved transversely and broke the shear keys, and another girder had a collapse of one span [3]. It can be found that the displacement between superstructure and substructure of the girder bridge is easy to occur in earthquakes. This characteristic is beneficial for protecting piers, considering that post-disaster retrofit of girder or bearing is much easier than that of the substructure. However, large displacement will induce falling of the main girder which may cause great loss of life and property. At the same time, it is not conducive to the rapid reuse of the bridge. Thus, research on reducing the seismic response of bridges and reasonably controlling the relative displacement of main girder and pier is of significance.

This study aims to evaluate the effectiveness of isolation bearings in controlling the response of a three span isolated reinforced concrete bridge and a suspension bridge subjected to strong earthquake. The response parameters considered for this study are the base shear in the piers, displacement and the acceleration of the bridge deck, pier displacement and the axial force in the cables. Three different isolation bearings are considered in this study, and effectiveness of these bearings in mitigating the seismic forces is described in this paper.

II. DESCRIPTION OF BRIDGES

A three span continuous concrete girder bridge [1] located in Victoria, British Columbia, Canada is considered in this study. The total length of bridge is 108 m which is divided into three unequal spans of length 40 m, 35m and 33 m respectively. The bridge consists of a 250 mm thick cast in situ concrete slab supported on three simply supported precast concrete I girders at 4.5 m spacing. The bridge superstructure rests on two pier caps of dimension 11.392 m ×1.6 m. Pier cap is supported on two-column bents with bent height of 15.5 m. Each column bent has two circular piers of diameter 1.5 m. The column spacing within a bent is 6.6 m. The piers are reinforced with 28M-30M longitudinal rebars and 15 M bars as spiral reinforcement. The existing bridge is not equipped with seismic isolation bearings. The concrete superstructure sits on elastomeric pads at each abutment and pier locations. Fig. 1 represents the general view of the considered RC bridge. The considered bridge is classified as a major route bridge according to the current Canadian Bridge Design Code (CHBDC).

The Forth Road Bridge [2] is a suspension bridge in east central Scotland. The main structure is a three-span suspension bridge. The bridge's central main span is 1,006 metres long, its two side spans are each 408 metres long, and the approach viaducts are 257 metres on the north side and 438 metres on the south side. The total width of the structure is 36 m. The total length is 2,512 metres. It was the longest suspension bridge span outside the United States and the fourth-longest span in the world at the time of its construction. The bridge's two main towers, with their distinctive “St Andrew's Cross” cross-bracing, support the majority of the weight of the suspended span. The two main cables sit on saddles at the summit of the towers, which pass the load back down to the ground. The entire suspended span and all the traffic is suspended from the bridge's two main cables. These sit on top of the main towers and side towers and are anchored into the rock on either shore. The deck of the bridge is suspended from the main cables by 768 steel hanger ropes. These measure 57 mm in diameter on the side spans and 48 mm in diameter on the main span. The shortest hanger is 2.4 metres long, the longest is 90 metres. Fig. 2 represents the suspension bridge considered for analysis. Table I represents the details of ground motions considered for analysis.

This study aims to evaluate the effectiveness of isolation bearings in controlling the response of a cable stayed bridge subjected to strong earthquake. The response parameters considered for this study are the base shear in the tower, displacement and the acceleration of the bridge deck and the axial force in the cables. Three different isolation bearings are considered in this study, and effectiveness of these bearings in mitigating the seismic forces is described in this paper.

Fig. 1 Reinforced Concrete Bridge

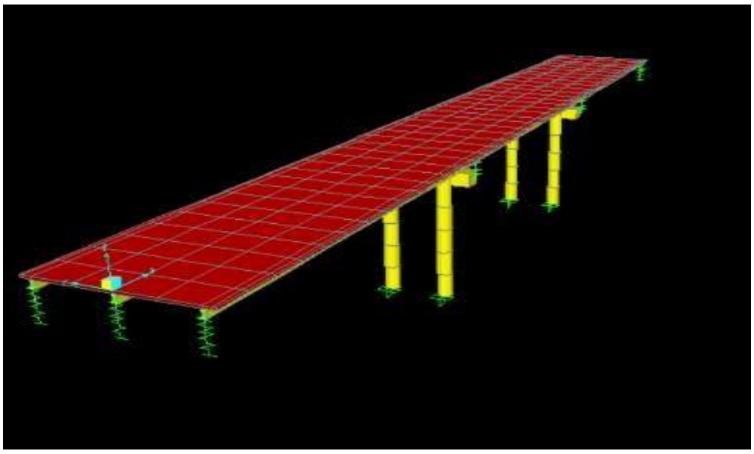

Fig. 2 Suspension Bridge

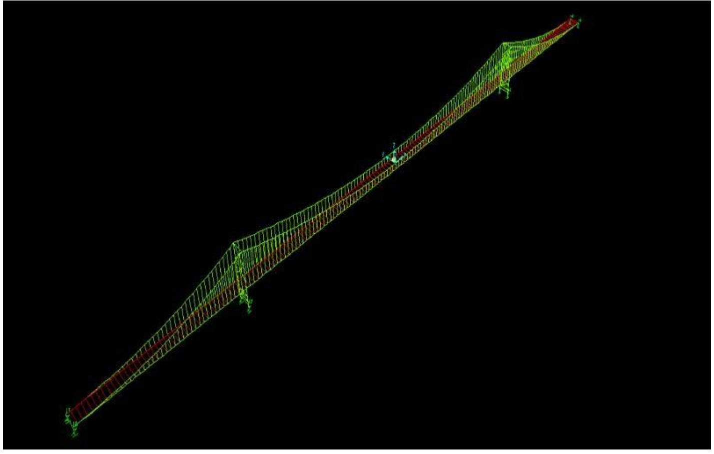

TABLE I DETAILS OF GROUND MOTIONS [10]

S. No.	**Earthquake**	**Year**	**Station**	**Magnitude (Richter Scale)**	**ation(s)**
1	Landers	1992	Indio Jackson road	7.2	22
2	Maule, Chile	2010	Talca	8.8	23
3	Northridge – 01	1994	Camarillo	6.7	16
4	Kobe, Japan	1995	Kobe University	6.9	19

III. FINITE ELEMENT MODELLING

The reinforced concrete and suspension bridges were modelled using SAP 2000 software [11]. The deck element of RC bridge was modelled using deck section available under the bridge component of SAP 2000 version 14. Piers were modelled under bent section component available in the software. The isolators were modelled through the link property. In the case of suspension bridge, the main towers were modelled using frame elements. The deck was modelled using shell element. The main cables and hanger ropes were defined using cable elements. The concrete girders were modelled as elastic beam elements for both the bridges. Load case was defined as non linear time history analysis with number of output time steps as 100. Three parameters are necessary to define the hysteresis behaviour of LRB such as, the initial stiffness, post-yield hardening ratio and post elastic stiffness. The FPS bearing was defined using friction pendulum bearing element available in SAP 2000. The model requires the definition of friction coefficient, the radius of curvature of the friction pendulum, and vertical force on the bearing. The parameters required to define the HDRB bearing are initial stiffness, post yield stiffness, damping coefficient and the damping ratio.

IV. SEISMIC ISOLATION BEARINGS

To investigate the effect of isolation bearings on the bridges, three different types of isolation bearings such as Lead Rubber Bearing(LRB), High Damping Rubber Bearing (HDRB) and Friction pendulum system (FPS) are considered in this study.

The Lead rubber bearing was invented in New Zealand [7] in 1975 and has been used extensively in New Zealand, Japan and the United States. The LRB is a laminated elastomeric bearing with a lead plug at its centre. The rubber in the isolator acts as a spring. It is very soft laterally but very stiff vertically. The high vertical stiffness is achieved by thin layers of rubber reinforced by steel shims. These two characteristics allow the isolator to move laterally with relatively low stiffness yet carry significant axial load due to their high vertical stiffness. The lead core provides damping by deforming plastically when the isolator moves laterally in an earthquake. In case of an earthquake, this bearing can separate top and bottom structure vibration, enlarge self vibration cycle and reduce seismic force. Besides, the lead core will be squeezed and yielded during the shear process to dissipate seismic force. The Fig. 3 represents the lead rubber bearing.

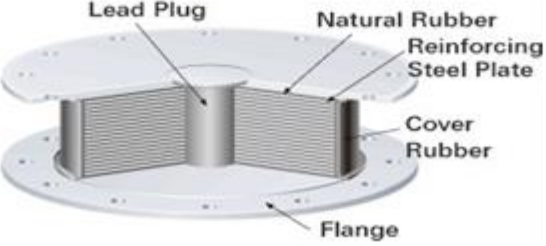

Fig. 3. Lead Rubber Bearing

The steel plates in the bearing, force the lead plug to deform in shear. This bearing provides an elastic restoring force and also, by the selection of an appropriate size for the lead plug, produces the required amount of damping. Table II represents the properties of Lead Rubber Bearing.

TABLE II PROPERTIES OF LRB

Parameter	**Value**
Post Elastic Stiffness	1.75 kN/mm
Effective Stiffness	3.6 kN/mm
d hardeningratio	0.19
Initial Stiffness, Ki	9.23 kN/mm

The basic components of the high damping rubber bearing are steel and rubber plates built in alternate layers as shown in Fig. 4.

Fig. 4 High Damping Rubber Bearing

The internal steel plates of HDRB, referred to as shims, provide a vertical stiffness that is several hundred times the horizontal stiffness. The steel shims prevent bulging of the rubber and provide a high vertical stiffness but have no effect on the horizontal stiffness, which is controlled by the low shear modulus of the elastomer. The dominant features of HDRB system are the parallel action of linear spring and viscous damping. The damping in the bearing is increased by adding extra-fine carbon block, oils or resins and other fillers.

Table III represents the properties of High Damping Rubber bearing.

TABLE III PROPERTIES OF HDRB

Parameter	**Value**
Effective stiffness	3.9 kN/mm
Post yield stiffness	1.7 kN/mm
d hardeningratio	0.15

The Friction Pendulum System (FPS) for seismic isolation of new and existing structures is increasingly used because of its advantageous characteristics, such as large deformation capacity, physical properties such as stability, durability, and rather good control of the fundamental vibration period. For relatively rigid structures, the seismic isolation by means of frictional systems is less sensitive to frequency content variationsof ground excitation and is characterized by high energy dissipation capability, thus effectively reducing the seismic actions in the structure with limited displacements. The Fig. 5 represents a Friction Pendulum System.

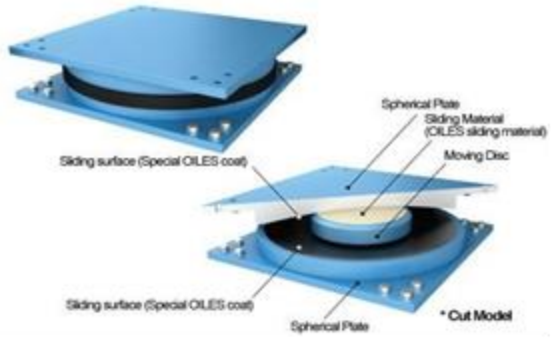

Fig. 5. Friction Pendulum System

Table IV represents the properties of Friction Pendulum System.

TABLE IV PROPERTIES OF FPS

Parameter	**Value**
Shear Stiffness	9 kN/mm
rvature radii of friction pendulum	2.5 m
Friction coefficient at fast velocities	0.06
Friction coefficient at slow velocities	0.03

V. MODAL ANALYSIS

One of the main design objectives of the isolation systems is to achieve a similar vibration period for all the bearings considered. These isolation bearings increase the fundamental period of the structure and thereby they prevent damage. Before performing nonlinear time history analysis, modal analysis of the bridge was conducted. The natural period of non isolated bridge under mode 1 for RC bridge is 1.026 seconds and that of LRB, HDRB and FPS is 1.531, 1.523 and 1.529 seconds respectively. Similarly in the case of suspension bridge the natural period of non isolated bridge under mode 1 for non isolated bridge is 1.131 seconds and that of LRB, HDRB and FPS is 1.510, 1.518 and 1.523 seconds. From table V and VI, it can be seen that all three isolated bridges have very similar modal behaviour, which ensures that their seismic response can be compared [8]. Tables V and VI represent the modal analysis results of RC and suspension bridges.

TABLE V MODAL ANALYSIS RESULTS OF RC BRIDGE

MODE solationSystem	**Mode 1 Period(s)**	**Mode 2 Period(s)**	**Mode 3 Period (s)**
LRB	1.531	1.321	1.028
HDRB	1.523	1.309	1.019
FPS	1.529	1.311	1.025
Without isolation	1.0267	0.8428	0.639

TABLE VI MODAL ANALYSIS RESULTS OF SUSPENSION BRIDGE

MODE solationsystem	**Mode 1 Period(s)**	**Mode 2 Period(s)**	**Mode 3 Period (s)**
LRB	1.510	1.319	1.008
HDRB	1.518	1.325	1.019
FPS	1.523	1.337	1.025
Without isolation	1.131	0.887	0.639

VI. RESULTS AND DISCUSSION

The performance of the three isolation systems under different ground motions considered are compared in terms of different structural response parameters such as maximum deck acceleration, maximum deck displacement, axial force in the cables and pier displacement. The seismic response of the isolated bridges subjected to the ground motions described above is compared through nonlinear time history analysis.

A. Base Shear

One of the main objectives of seismically isolated bridges is to decouple the superstructure from substructure thereby reducing the seismic demand on the bridge piers. This reduced base shear demand can reduce the overall dimension of the substructure including the foundation resulting in cost reduction. In the case of RC bridge, the maximum value of the base shear was observed under Maule earthquake with a value of 9627.2 kN and was dropped to 6008.9 kN when lead rubber bearing was utilized in the bridge. Seismic isolation was found to be very effective in reducing the pier base shears. The maximum reduction in base shear was observed in bridge implemented with LRB system and the percentage reduction in base shear was 12.1 % and 8.2 % compared to HDRB and FPS system. A minimum of 20 % reduction in base shear is achieved with the use of isolation system in the RC bridge.

In the case of suspension bridge, the base shear was reduced from 9476 kN to 5763 kN with the use of LRB system. The percentage decrease in base shear of the isolated bridge in comparison with the non isolated bridge is 21.26%. The percentage reduction in base shear of the bridge with LRB when compared to the HDRB and FPS system is 15.43 % and 19.48 % respectively.

Out of three isolation bearings considered, base shear was reduced effectively by the lead rubber bearing in all ground motions considered. Fig.6 and Fig.7 represent the comparison of base shear values of RC and suspension bridges under different ground motions.

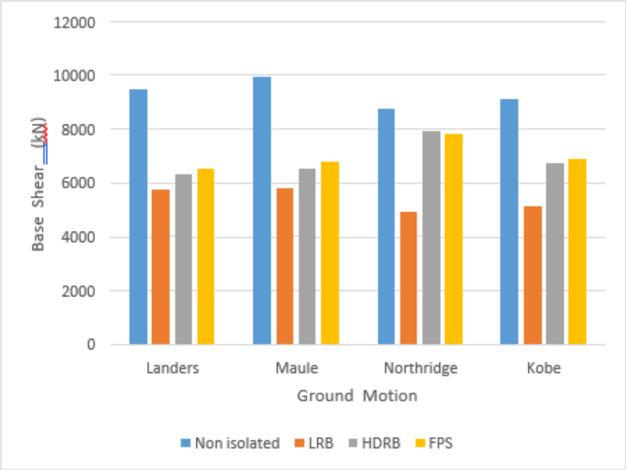

Fig. 6 Comparison of base shear values of RC bridge

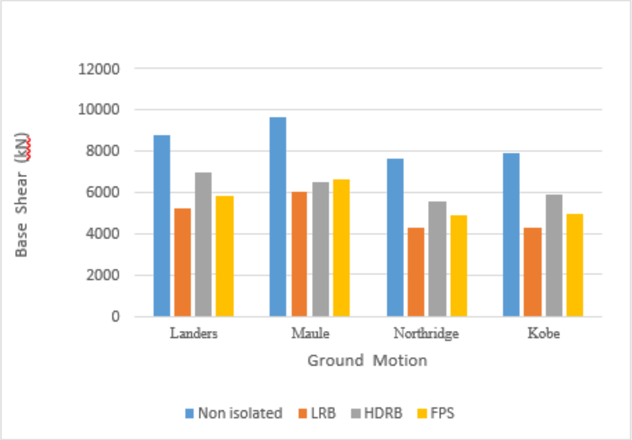

Fig. 7 Comparison of base shear values of suspension bridge

Table VII represents the summary of seismic response of RC bridge.

TABLE VII SUMMARY OF SEISMIC RESPONSE OF RC BRIDGE

Ground Motion	**Landers**				**Maule**				**Northridge**				**Kobe**			
Response	Non isolated	LRB	HDRB	FPS	Non isolated	LRB	HDRB	FPS	Non isolated	LRB	HDRB	FPS	Non isolated	LRB	HDRB	FPS
se Shear (kN)	8763	5213	6931	58466	9627	6008	7612	6613	7628	4271	5581	4877	7913	4308	5876	4944
Deck Displacement (cm)	3.9	9.3	8.1	7.7	4.8	11.9	10.4	9.8	2.8	6.4	5.3	4.6	3.2	7.7	6.2	5.4
Deck Acceleration (m/s^2)	10.1	4.62	4.21	3.31	12.3	5.1	4.9	2.7	9.12	3.1	2.9	2.6	9.23	3.5	3.1	2.7
Pier Displacement (mm)	22.7	46.2	39.7	31.8	32	52.7	49	40.9	20.9	41.2	36.2	29.6	21.6	32.1	30.7	28.1

A. Maximum Deck Acceleration

Another major objective of using seismic isolation bearing is to reduce the acceleration of the bridge deck induced by the ground motion. The non-isolated bridge experienced larger deck accelerations for all the ground motions as compared to the bridge with isolation system. Typically, the deck acceleration is proportional to the seismic force applied to the structure. For the non isolated bridge in case of RC bridge, the maximum value of deck acceleration was observed under Maule ground motion with a value of 12.3 m/s^2. Bridge with FPS system experienced a minimum deck acceleration. The minimum percentage reduction in deck acceleration with the use of isolation bearings is 42.3%. The percentage reduction of deck acceleration of FPS system when compared to LRB and HDRB system is 39.03% and 34.22 % respectively.

In case of suspension bridge the maximum reduction in deck acceleration with the use of isolation bearings is 39.13 %. The deck acceleration was effectively reduced by the HDRB system than the other two isolation bearings considered. Fig. 8 and Fig. 9 represent the comparison of deck acceleration values of RC and suspension bridges under Landers ground motion.

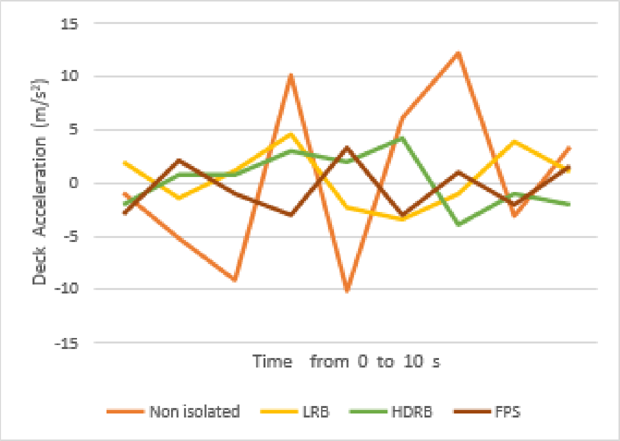

Fig. 8 Variation of Deck Acceleration with respect to time of RC bridge corresponding to Landers ground motion

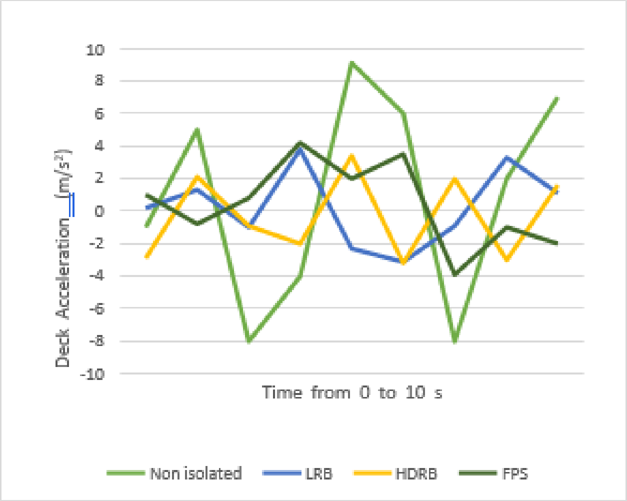

Fig. 9 Variation of Deck Acceleration with respect to time of Suspension bridge corresponding to Landers ground motion.

Table VIII represents the summary of seismic response of suspension bridge.

TABLE VIII SUMMARY OF SEISMIC RESPONSE OF SUSPENSION BRIDGE

Ground Motion	**Landers**				**Maule**				**Northridge**				**Kobe**			
Response	Non Isolated	LRB	HDRB	FPS	Non Isolated	LRB	HDRB	FPS	Non Isolated	LRB	HDRB	FPS	Non Isolated	LRB	HDRB	FPS
se Shear (kN)	9476	5764	6321	6543	9934	5802	6542	6821	8745	5908	6645	6803	9121	5131	6751	6878
Deck Displacement (cm)	2.8	9.2	11.9	6.3	3.7	10.5	12.1	7.4	2.1	9.7	8.3	5.8	2.6	8.8	11.6	7.1
Deck Acceleration (m/s^2)	9.1	3.8	3.4	4.2	10.2	4.9	4.5	5.1	8.6	3.8	3.2	4.8	9.4	4.2	3.9	4.7

B. *Maximum Deck Displacement*

Since the isolation bearings increase the flexibility of the structure, the maximum deck displacement of the isolated bridge is larger than the non-isolated bridge under all ground motions. The maximum longitudinal displacement of the deck is increased from 4.8 cm to 11.9 cm after implementation of the base isolation system in the RC bridge; hence an increment of 59.7% is observed. The deck displacements are increased because the isolators changed the boundary conditions of the bridge, at which it removed the transverse restraints of the bridge at the abutments and changed the deck-pier configuration from a rigid connection to a moveable connection. LRB bearing has resulted in maximum deck displacement compared to the other considered bearing. FPS has the lowest deck displacement values. The percentage increase in deck displacements of LRB, HDRB and FPS systems when compared to non isolated bridge in the case of RC bridge is 58.1%, 51.8% and49.3% respectively. Therefore, despite the deck displacement increments in the isolated bridge, these displacements were limited to the design displacements obtained by the simplifiedanalysis of the bridge. Figures 10 and 11 represents the comparison of deck displacement values corresponding to different ground motions. In case suspension bridge the deck displacement increased from 3.7 cm to 12.1cm when the isolation system was utilised in the bridge. The maximum percentage increase in deck displacement of the isolated bridge in comparison with the non isolated one is 69.42 %. The maximum values of deck displacement was observed in bridge with HDRB system.

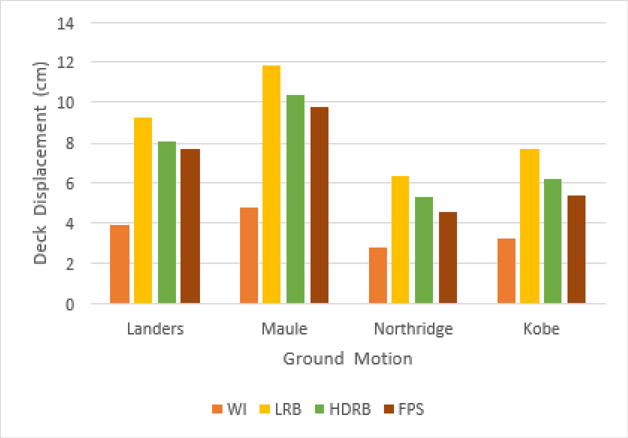

Fig.10 Comparison of deck displacement values of RC bridge

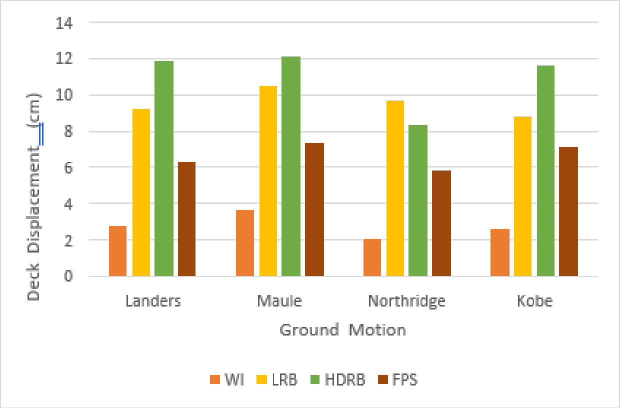

Fig.11 Comparison of deck displacement values of suspension bridge

C. *Axial Force in the Cables*

The utilization of base isolation system resulted in a remarkable minimization of axial force in the cables of the suspension bridge. The maximum reduction in axial force of the cables with the use of isolation bearing is 33.12 %. The axial force in cables was effectively reduced by the HDRB bearing than the other bearings considered.

D. *Maximum Pier Displacement*

Since isolation bearings increase the flexibility of the structure, it is expected that the pier displacement will increase for an isolated bridge. In case of RC bridge, among the three isolated bridges, the LRB isolated bridge pier experienced maximum average displacement of 52.7 mm under Maule ground motion. The maximum percentage increase in pier displacement when compared to the non isolated bridge is 45.7%.The lead rubber bearing system experienced higher pier displacement when compared to the other two bearings. The maximum value of pier displacement of a non isolated bridge is 32 mm. The percentage increase in pier displacement of LRB system when compared to the HDRB and FPS system is 14.06 % and 31.18% respectively.

CONCLUSIONS

In this study, the seismic behaviour of RC bridge and suspension bridges equipped with three different types of isolation bearings have been investigated. The isolators have been designed for the strongest earthquake and were implemented at abutments, deck-pier connections in RC bridge and along tower to foundation connection in the case of suspension bridge. The bridge seismic responses have been evaluated for four ground motions. In line with this purpose, a 3D finite element model of the bridges have been developed and the nonlinear dynamic time-history analysis of the bridges have been performed. From the detailed analysis, the implementation consequences of the base isolation system in RC bridge and suspension bridge led to the following conclusions;

- The isolation system was significantly capable to reduce the base shear and deck acceleration of the bridge under all considered ground motions.
- The reduction of shear force proved that the isolation system is able to dissipate the seismic forces transmitted

from substructure to superstructure and hence, reduced the occurrence of damage to the superstructure. LRB system was most effective in reducing the base shears than the other two systems.

- The implementation of the isolation system between superstructure and substructure increased the deck flexibility, leading to an increase in the values of deck displacement. Deck displacement was minimum in the bridges with FPS system.
- The axial force in the cables of suspension bridge were reduced upto 33% with the use of isolation bearings.
- The deck acceleration was substantially reduced with the use of isolation bearings. In case of RC bridge, the FPS bearing reported lowest values of deck acceleration and HDRB bearing has resulted in lowest values in the case of suspension bridge.
- The best suited bearing for suspension bridge is HDRB system whereas in case of RC bridge it is FPS system.

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