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Seismic response of a continuous bridge with bearing protection devices

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ABSTRACT

Unseating of bridges during earthquakes results from the failure of bearings and insufficient seat length. In case of elastomeric bearings, large deformations of the superstructure occur, under severe earthquake ground motions and additional protection measures are necessary. The combination of a displacement restraining device with the elastomeric bearing can prevent bearing failure. This paper evaluates the performance of four different types of protection devices to limit the displacement of the superstructure during earthquakes: (1) rigid stopper device, (2) yielding stopper device, (3) steel restrainer, and (4) superelastic shape memory alloy (SMA) restrainer. Analytical models for all the protection devices have been developed and seismic response of an existing bridge with elastomeric bearings and different protection devices has been evaluated for five strong ground motion records scaled in the frequency domain. The results show that all the protection devices have comparable performance in preventing the failure of bearing during an earthquake.

1. Introduction

Failure of bridges due to excessive displacement of superstructure or inadequate seat length at the pier or abutment is a common phenomenon during earthquakes. In case of elastomeric bearings [1–3], which do not have any energy dissipating characteristics, the displacement during a severe earthquake is quite large and may exceed the capacity of the bearing, resulting in failure of the bearing [4] and unseating of the superstructure. Measures to reduce the chances of collapse due to unseating at the supports have been available for many years [5]. But, in spite of that, the collapse of the bridges due to unseating continues and the Chi–Chi [6], Kobe [7], San Fernando [8] and Northridge [9] earthquakes have shown several examples. Therefore, there is a definite need to explore better methods of protection of bridges against unseating failure during earthquakes.

Restrainers and stoppers are used as the protection devices to prevent the failure of bridges due to unseating [10,11]. Various design approaches for restrainers are available in literature [12–14] and design codes [15–17]. In all the approaches, the focus is on the prevention of falling of the superstructure and no attention is given to the prevention of the failure of bearings. In the present study, the possibility of restrainers designed to prevent failure of the bearings during severe earthquakes has been explored. Using this approach, the bearing protection devices can be designed for new bridges, as well as, for existing bridges. In case of existing bridges, this method can be used if the existing bearings are not able to accommodate large displacement due to strong earthquake. In case of older bridges, the most widely used bearings are elastomeric bearings and these are generally designed only for movements arising due to temperature, creep and shrinkage. Use of restrainers/stoppers can be an effective technique to prevent failure of these bearings during earthquake.

The proposed method can also be useful for new bridges, if the designer does not have confidence in the use of isolation or energy dissipation devices and is inclined to use conventional elastomeric bearings. If the elastomeric bearing is designed for severe earthquake (MCE) it may lead to very large size of the bearing which is not practically acceptable in respect of required pier cap dimension. Reduction of the size of the elastomeric bearing may lead to failure, during an MCE level of earthquake. Therefore, restrainers/stoppers can be used with the elastomeric bearings to prevent failure of the bearings during severe earthquake.

Several types of devices, such as, steel rods, steel cables [18,19] and dampers have been used as the unseating protection devices for bridges. Shape Memory Alloy (SMA) has also been used in bridges as an unseating protection device [20–25]. Various devices have relative merits and the designer has difficulty in selecting the most appropriate device.

In this paper, the comparative performance of different types of unseating protection devices has been studied for a continuous bridge. All the devices have been designed to prevent failure of bearings. Four types of devices have been considered in the study: (1) rigid stopper, (2) yielding stopper, (3) traditional steel

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Nomenclature

DBE	Design Basis Earthquake
MCE	Maximum Considered Earthquake
F	Force
F_y	Yield Force of the Protection Device
K	Stiffness of the Protection Device
Δ	Displacement
Δ_i	Initial Slack/gap in the Protection Device

restrainers, and (4) Shape Memory Alloy (SMA) restrainer. A three dimensional model of the bridge has been developed using the software SAP2000 Nonlinear [26]. A set of five accelerograms, compatible with the site specific design response spectrum has been used for study of the seismic response.

2. Unseating protection devices

Different types of unseating protection devices, viz. rigid stopper, yielding stopper, steel restrainer and SMA restrainer, have been explored in the past. All these devices can be used along with the elastomeric bearings. The rigid stopper has a very high strength and stiffness and is provided with a gap from the superstructure, coming into action after a certain amount of displacement of the elastomeric bearing and stopping further displacement (Fig. 1). A yielding stopper [27] and a steel restrainer have a similar behaviour but the initial stiffness and yield strength are different for the two devices. These devices yield at a particular force, and then undergo strain hardening (Fig. 2). In the case of SMA restrainer devices [28–33], Nitinol shape memory alloy is the most commonly used material. Shape memory alloys display several remarkable characteristics like thermo-mechanical phase change, shape memory effect, superelastic effect and high damping. Shape memory effect has been observed when the alloy is loaded at a temperature below a specific temperature (martensite finish temperature). In this case, the residual strain can be recovered by heating the material to a temperature above the austenite finish temperature. A superelastic effect (Fig. 3) has been observed when the material is loaded at a temperature above the austenite finish temperature. In this case, during unloading, the material recovers all of its residual strain. The superelastic effect in the shape memory alloy is the property used in restrainer devices.

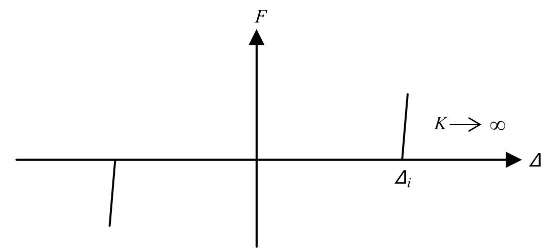

Fig. 1. Force–displacement behaviour of a rigid stopper device.

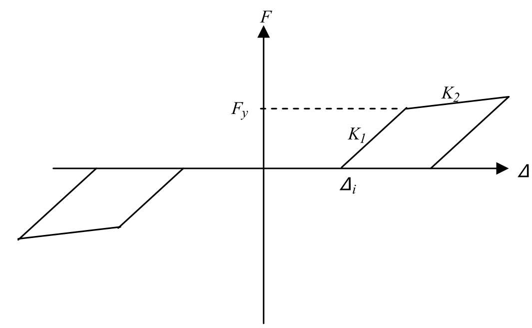

Fig. 2. Force–displacement behaviour of yielding stopper and steel restrainer devices.

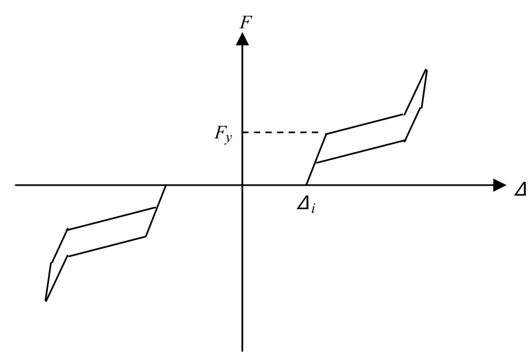

Fig. 3. Force–displacement behaviour of superelastic SMA restrainer device.

3. Bridge considered for the study

An existing three span railway bridge, situated in Northern India, has been considered in the present study. The site of the bridge falls in the Seismic Zone IV of the Indian seismic zoning [34]. It is a continuous prestressed concrete box girder bridge, having a total length of 192 m with the main span of 80 m and two end spans of 56 m each (Fig. 4). The cross-sectional details of box girder are shown in Fig. 5. The height of the piers is 36.36 m. The piers have a hollow circular section with an external diameter of 6.5 m and thickness of 0.5 m. The piers rest on rocky strata.

4. Modelling and analysis

The bridge structure has been modeled (Fig. 6) using the software SAP2000 Nonlinear. The superstructure and the piers have been modeled using 3D frame elements with mass lumped at discrete points. Since the piers are resting on rock, these have been modeled as fixed at the base. The abutments have been assumed to be rigid. To model the spatial placement of bearings across the section, horizontal cross rigid links as shown in Fig. 6 have been used. Elastomeric bearings have been modeled using elastic link elements. The rigid stopper has been modeled using a link element having high stiffness, whereas the yielding stopper and the steel restrainer have been modeled by elasto-plastic bi-linear link elements. The behaviour of the superelastic SMA restrainer (Fig. 7(a)) has been modeled through the parallel combination of two elastic multilinear link elements and one plastic bilinear element, which is in series with a hook element (Fig. 7(c)). The multilinear link elements have been assigned elastic stiffness in both the horizontal directions and are rigid in the vertical direction. The schematic modeling of the superelastic SMA restrainer in both the longitudinal and transverse directions has been shown in Fig. 7(b).

The site-specific design response spectra for Maximum Considered Earthquake (MCE) and Design Basis Earthquake (DBE) have been considered in the study. Fig. 8 shows the site specific design response spectra for 5% damping. Recorded time histories for five different earthquakes have been used and scaled in the frequency domain, to simulate the design response spectrum [35], preserving their phase information. The scaled time histories for MCE loading condition have been shown in Fig. 9. The recorded earthquakes considered are: (1) Elcentro (1940), (2) Kobe (1995), (3) Northridge (1994), (4) Loma Prieta (1989) and (5) San Fernando (1971). The details of the earthquake records have been presented in Table 1.

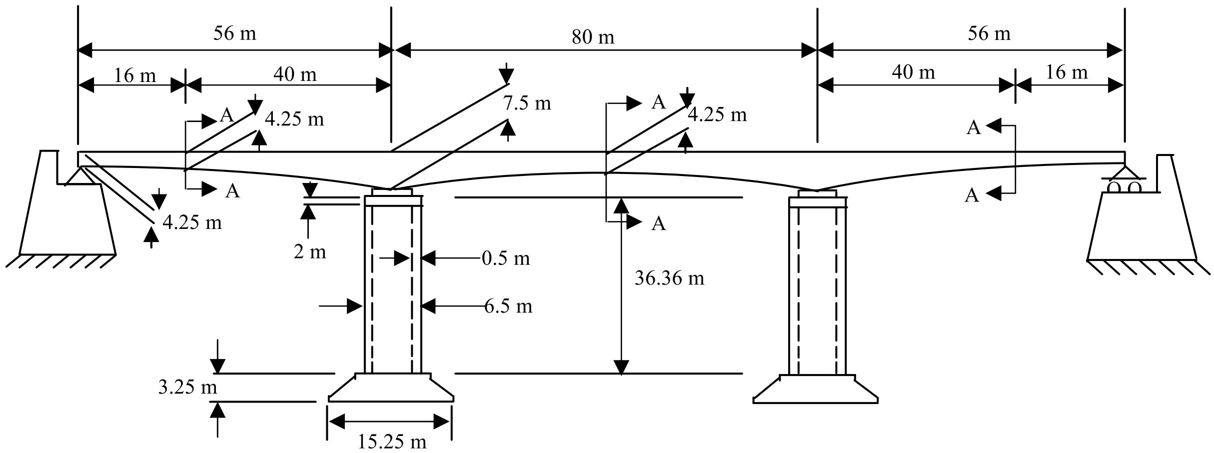

Fig. 4. Continuous bridge.

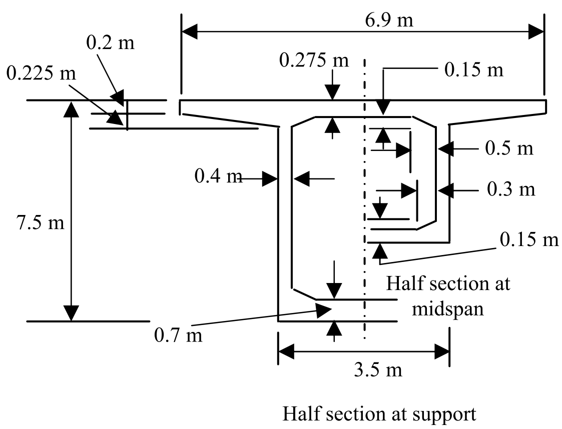

Fig. 5. Box-girder section (A–A).

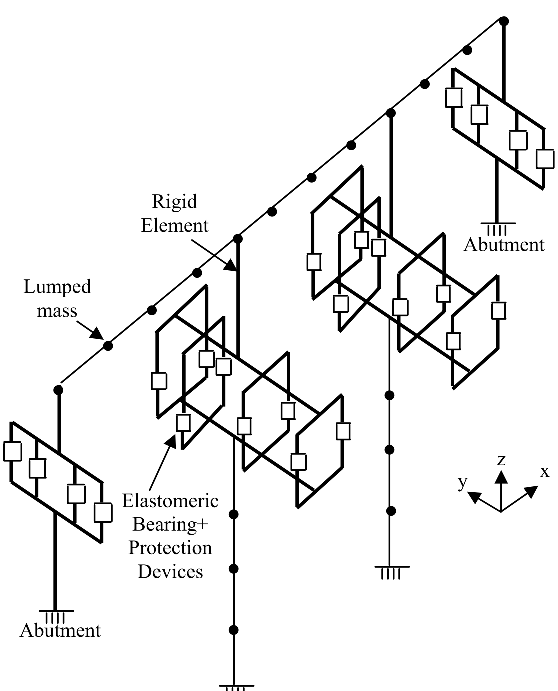

Fig. 6. 3D model of the continuous bridge.

First, free vibration analysis of the bridge was performed to evaluate the dynamic characteristics. Linear Time History Analysis was performed in the case of Elastomeric Bearings, while Non-linear Time History Analysis was performed in the case of Elastomeric Bearings with protection devices. It has been observed that the piers provided in the bridge have much larger strength than the seismic demand, and do not yield even under MCE. Therefore, the nonlinearity in the bridge is limited to the protection devices only.

5. Design of bearing protection devices

In the present study, the dimensions of the elastomeric bearings have been considered as 400 × 800 × 84 mm, according to the guidelines of the Indian code of practice [36]. The allowable displacement of the elastomeric bearing has been calculated based on different criteria (maximum strain criteria, rollover at the edges and criteria for delamination due to fatigue, etc.) as provided in various codes [36–38]. The minimum of the values obtained from different criteria has been considered as the displacement limit for the elastomeric bearing. For the present case, the displacement limit has been obtained as 42 mm. The analysis shows that the bearing displacement for an MCE level earthquake ground motion crosses this limit. Therefore, appropriate bearing protection measures are necessary.

A number of parameters are to be decided in the design of bearing protection devices. One of the important criteria for designing protection devices is the selection of the level of earthquake ground motion. Since the devices should perform satisfactorily to avoid even in case of a Maximum Considered Earthquake (MCE), the design has been carried out for MCE. The design parameters for the bearing protection devices are initial slack/gap, stiffness and yield force. These parameters are interrelated and affect the seismic performance in a complex manner. Further, to have a fair comparison of the relative performance of different devices, an optimum combination of different design parameters in case of each device is required to be obtained. In the present study, optimum combinations of various design parameters for different systems have been obtained using a sensitivity study and the performance of different systems has been compared for the obtained optimum design.

6. Parametric study

First, a sensitivity study of the bridge response for different bearing protection devices with varying yield force, initial stiffness, length and initial slack/gap has been performed to obtain the optimum combinations of design parameters for the individual devices. The optimal combination of the design parameters is the

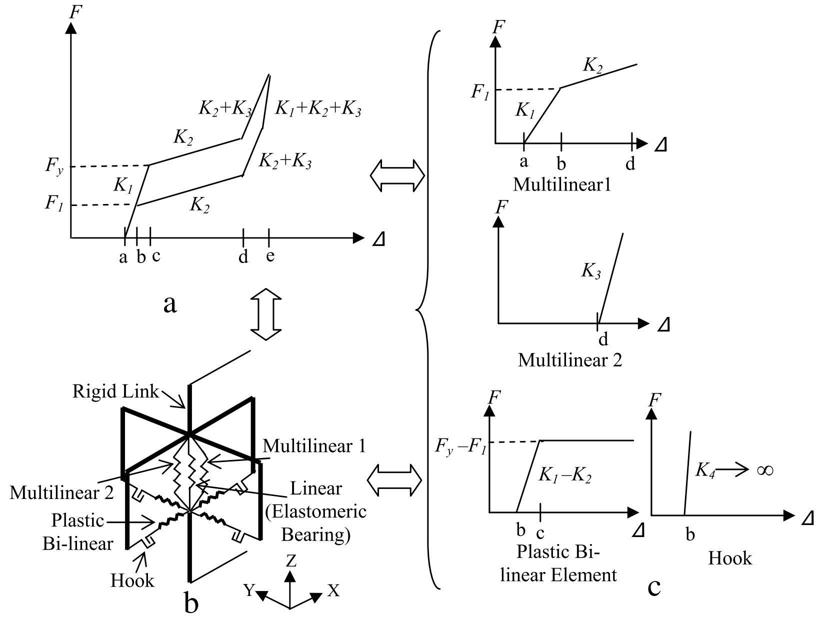

Fig. 7. Modelling of superelastic SMA restrainer device (a) Force–displacement behaviour of restrainer, (b) Schematic arrangement of constituent elements, and (c) Force–displacement behaviour of constituent elements.

Table 1
Recorded ground motions considered for the study.

Record	Event	Year	Magnitude	Station	Orientation	PGA(g)	Distance-to-fault (km)
1	Elcentro	1940	7.0	117 El Centro Array #9	IMPVALL/I-ELC180	0.313	8.3
2	Kobe	1995	6.9	0 KJMA	KJM000	0.821	0.6
3	Northridge	1994	6.7	24278 Castaic–Old Ridge Route	ORR090	0.568	22.6
4	San Fernando	1971	6.6	24278 Castaic–Old Ridge Route	ORR021	0.324	24.9
5	Loma Prieta	1989	6.9	57007 Corralitos	CLS000	0.644	5.1

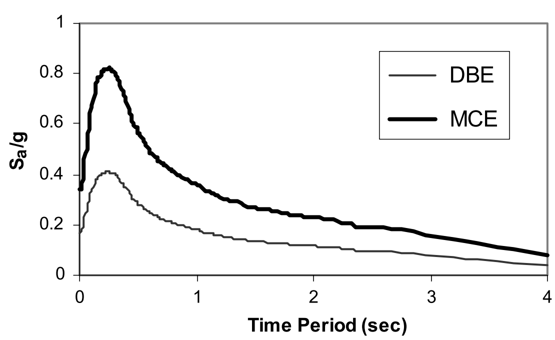

Fig. 8. Site specific design response spectrum for 5% damping.

one satisfying the maximum displacement limit of the bearing and resulting in the minimum shear force in the piers. As separate restrainers are provided for the longitudinal and transverse directions, the analysis has been performed independently, in longitudinal and transverse directions. Then a comparative study of various systems, has been performed with the obtained optimal combinations of design parameters. The average maximum response of the bridge for the five scaled accelerograms, described earlier has been compared for different devices.

6.1. Dynamic characteristics of the bridge

Table 2 shows the dynamic characteristics of the bridge considered. Since the abutments are much stiffer than the piers, these provide higher resistance to superstructure displacement as compared to the piers. Further, as the superstructure is much more rigid in longitudinal direction, than in the transverse direction, it results in longer period of vibration in the transverse direction. The difference in the dynamic characteristics of the bridge in the two directions, requires different designs of bearing protection devices in the two directions.

6.2. Response sensitivity and optimum design parameters

Fig. 10 shows the variation of the seismic response of the bridge for the superelastic SMA restrainers along the longitudinal and transverse directions. The design parameters for SMA restrainers are initial slack, length and cross-sectional area. Initial stiffness and yield force depend on the chosen sizes. The yield strength (F_y) of the Nitinol shape memory alloy have been considered as reported by DesRoches and Delemont [29]. The values of K_2 and K_3 have been considered as 0.07 and 0.45 times, respectively of initial stiffness [29]. The strain levels of the device at points b, c, d and e (Fig. 7) have been considered as 0.5%, 1.5%, 5% and 8%, respectively, as per DesRoches and Delemont [29]. The recoverable strain has been considered as 8%. The optimum values of different parameters of the device have been decided through a trial process. In the process, first the values of F_y and the length of restrainer have been chosen and the value of initial stiffness, K_1 has been obtained using the required cross-section and the chosen length. The combination of slack, F_y and K_1 resulting in bearing displacement close to the maximum limit, and the minimum shear force in piers was selected for further comparative study.

In sensitivity analysis, effect of variation of each design parameter has been studied, keeping the other parameters constant (Fig. 10). As expected, the bearing displacement increases with increase in slack and length of restrainer. For increasing the value of yield force, F_y, two cases are considered. In the first case,

Table 2
Dynamic characteristics of the bridge.

Mode	Period (s)	Mass participation factor (%)	Direction of mode shape
1	1.64	67	Trans.
2	1.28	65	Long.
3	0.23	7.1	Trans.
4	0.22	6.4	Long.
5	0.19	7.6	Long.
6	0.06	4.1	Trans.

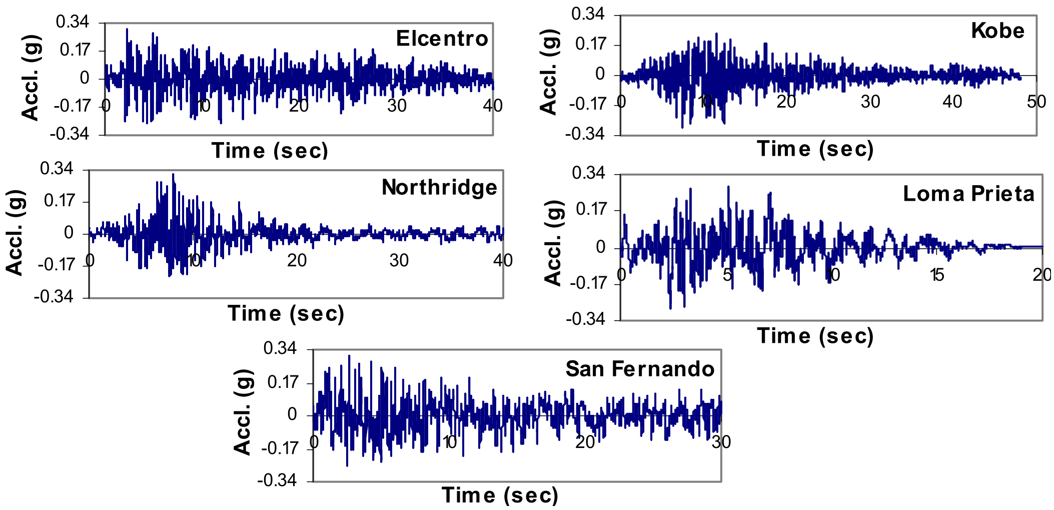

Fig. 9. Ground acceleration time histories scaled to MCE spectrum.

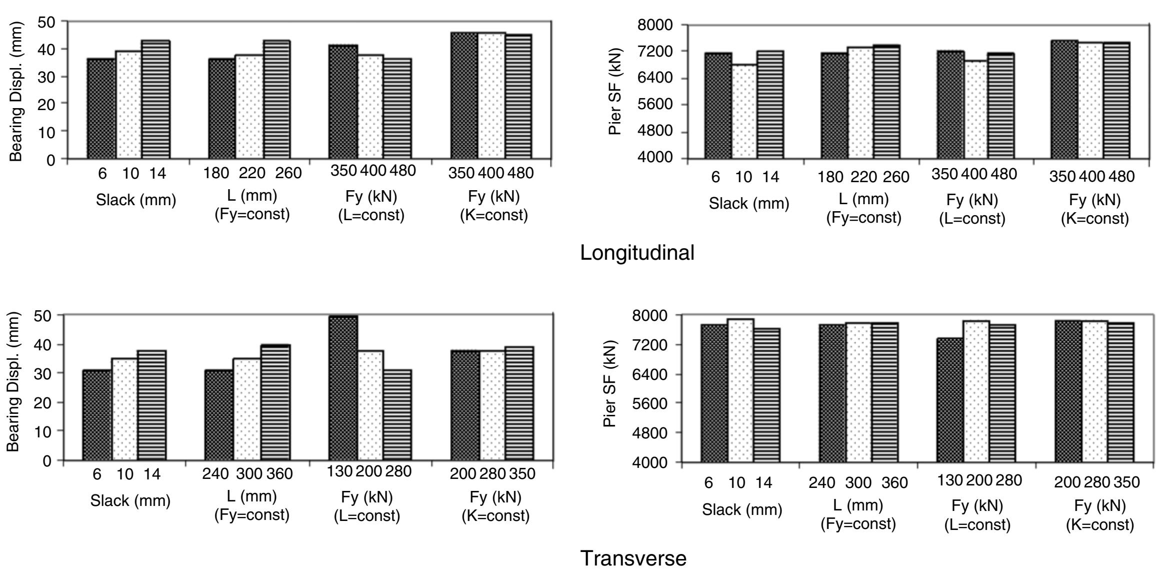

Fig. 10. Variation of response with SMA device.

the length of restrainer is kept constant so that increase in F_y results in increased cross-section and hence in increased stiffness. In the second case, F_y is increased, keeping the stiffness constant, requiring increase in the length of restrainer. In the first case, the bearing displacement decreases with increase in F_y, but in the second case, bearing displacement is insensitive to F_y, as the effects of increased yield force and length nullify each other. It can also be noticed that the pier shear force does not change significantly with the design parameters for the SMA restrainers and it is difficult to identify a pattern.

Fig. 11 shows the variation of the seismic response of the bridge with the design parameters of steel restrainer, along the longitudinal and transverse directions. In this case also, the process similar to that for SMA restrainer was adopted for sensitivity analysis. The effect of various parameters on bearing displacement is also similar to that in case of SMA restrainer. However, it has been noticed that in this case, the pier shear force is relatively insensitive to the design parameters in the longitudinal direction, but in the transverse direction, the variation of pier shear force is opposite to that of bearing displacement. In the transverse direction, the pier shear force decreases with increase in the length of the device and increases with increase in the yield force of the device.

Fig. 12 shows the variation of the seismic response of the bridge for the yielding stopper device, along the longitudinal and transverse directions. It can be observed that the governing parameters

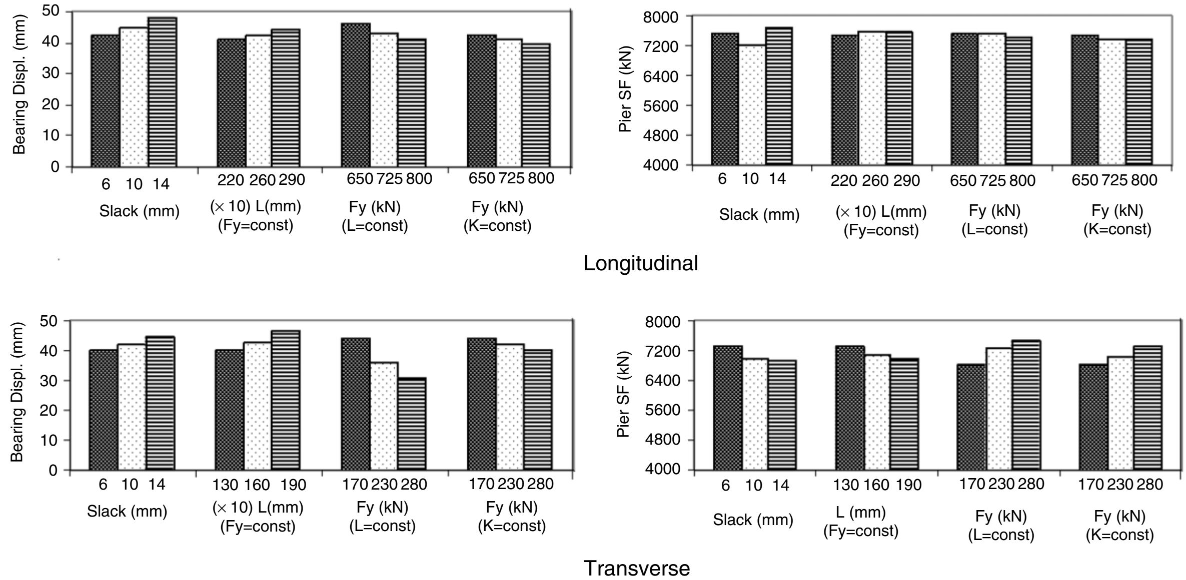

Fig. 11. Variation of response with steel restrainer device.

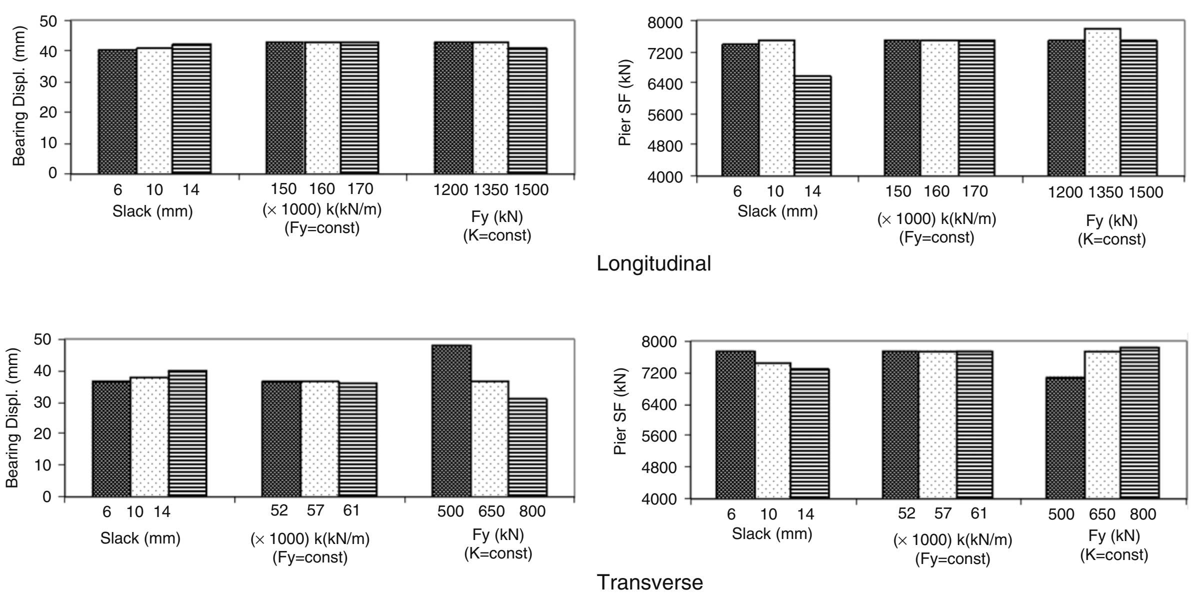

Fig. 12. Variation of response with yielding stopper device.

Table 3
Optimal design parameters of protection devices for MCE loading condition.

Direction	Protection devices	Bearing displacement (m)	Initial stiffness (kN/m)	Length (m)	Yield force (kN)	Slack (m)
Long.	SMA	0.042	145758	0.220	481	0.006
Long.	Steel restrainer	0.042	190000	2.1	800	0.006
Long.	Yielding stopper	0.042	180000	–	1500	0.014
Trans.	SMA	0.042	52407	0.360	283	0.006
Trans.	Steel restrainer	0.042	106970	1.32	283	0.006
Trans.	Yielding stopper	0.042	56784	–	650	0.014

in this case are the initial gap between the superstructure and stopper and the yield force. Stiffness of the stopper has relatively insignificant effect on the bridge response. Further, as expected, the bearing displacement increases with the initial gap and decreases with the yield force, the shear force in the pier has just opposite pattern of variation.

Table 3 shows the obtained optimal design parameters for different types of protection devices, for MCE loading condition. In case of rigid stopper, the stiffness and yield force have been assigned very high values and the slack (gap) has been considered as 42 mm.

6.3. Seismic response of the bridge with different protection devices

Tables 4 and 5 show the seismic response of the bridge along longitudinal direction for MCE and DBE loading conditions, respectively. It can be observed from the tables that in case of all the protection devices, the bearing displacement can be controlled

Table 4
Seismic response of the bridge along longitudinal direction for MCE.

Protection device	Bearing displ. (m)	Pier displ. (m)	Pier shear force (kN)	Pier bending moment (kN m)	Abutment shear force (kN)	Energy dissipated (kN m)
No protection	0.125	0.025	5704	111666	2182	0
Rigid stopper	0.042	0.014	4732	77453	31269	0
Yielding stopper	0.042	0.024	6579	121605	6238	2512
SMA	0.042	0.027	7341	134364	8333	2750
Steel restrainer	0.042	0.028	7337	136650	5811	2624

Table 5
Seismic response of the bridge along longitudinal direction for DBE.

Protection device	Bearing displ. (m)	Pier displ. (m)	Pier shear force (kN)	Pier bending moment (kN m)	Abutment shear force (kN)	Energy dissipated (kN m)
No protection	0.062	0.012	2852	55 833	1 091	0
Rigid stopper	0.042	0.009	2598	45 632	13 430	0
Yielding stopper	0.028	0.013	3960	71 186	5 088	483
SMA	0.022	0.015	4096	74 939	3 661	700
Steel restrainer	0.018	0.011	3486	60 337	3 589	593

Table 6
Seismic response of the bridge along transverse direction for MCE.

Protection device	Bearing displ. (m)	Pier displ. (m)	Pier shear force (kN)	Pier bending moment (kN m)	Abutment shear force (kN)	Energy dissipated (kN m)
No protection	0.128	0.055	5995	163 843	1643	0
Rigid stopper	0.042	0.075	7531	220 135	5497	0
Yielding stopper	0.042	0.068	7268	206 189	2445	729
SMA	0.042	0.073	7766	214 613	2562	1400
Steel restrainer	0.042	0.068	7288	203 260	2283	1295

Table 7
Seismic response of the bridge along transverse direction for DBE.

Protection device	Bearing displ. (m)	Pier displ. (m)	Pier shear force (kN)	Pier bending moment (kN m)	Abutment shear force (kN)	Energy dissipated (kN m)
No protection	0.064	0.028	2997	81 922	821	0
Rigid stopper	0.042	0.035	3595	102 261	2140	0
Yielding stopper	0.023	0.037	3665	109 072	1470	63
SMA	0.018	0.035	3766	104 376	1263	300
Steel restrainer	0.015	0.035	3699	103 865	1332	202

within the acceptable limit for the bearing. But, this results in higher pier and abutment forces. For the same amount of bearing displacement, the rigid stopper has resulted in 42%–50% less pier displacements and 28%–43% less pier forces, for MCE and 18%–40% less pier displacements and 25%–39% less pier forces for DBE, as compared to other devices. However, this is at the cost of increased abutment forces. The rigid stoppers at the rigid abutments, transfer larger forces to the abutments, and, therefore, the pier forces in the bridge are reduced. There is no permanent displacement of the superstructure in the present case, as the devices are connected along with the elastomeric bearings, which behave elastically.

Among the three protection devices, other than the rigid stopper, yielding stopper device shows slightly better performance in case of MCE loading. The yielding stopper device results in minimum pier displacement and minimum pier forces. Under DBE loading, the performance of the steel restrainer device is relatively better than the SMA restrainer and yielding stopper devices, as it results in minimum displacement of the pier and the Bearing, and minimum forces in pier and abutment. However, it is to be noted that SMA device has higher energy dissipation (Tables 4–7) as compared to all other protection devices and has additional protection against higher ground shaking levels due to strain hardening effect at larger strains.

Tables 6 and 7 show the seismic response of the bridge along transverse direction for MCE and DBE loading conditions, respectively. In transverse direction, the relative performance of rigid stopper is not as good as in the longitudinal direction. This is due to flexibility of the superstructure in transverse direction. The performance of the other devices is also comparable with the SMA device, resulting in only marginally higher pier displacement and pier forces, as compared to the steel restrainer and yielding stopper.

7. Conclusions

In this paper, the relative performance of different types of bearing protection devices has been studied for an existing three span continuous bridge. The bridge response has been found to be sensitive to the design parameters of the protection devices and the optimum combinations of design parameters for each device, restricting the bearing displacement to the desired limit and resulting in the minimum forces in piers and abutments, have been obtained using a trial process. All the four devices considered in the study, viz. rigid stoppers, yielding stoppers, steel restrainers, and SMA Restrainers have restricted the peak displacement in the conventional Elastomeric bearings to the safe design limits, however, with an increase in the pier/abutment forces. It is interesting to note that for the optimum design, all the devices have comparable performance. The SMA Restrainer results in marginally higher pier/abutment forces but have better energy dissipation and additional protection against higher ground shaking levels due to strain hardening at higher strain levels.

References

[1] Mori A, Carr AJ, Cooke N, Moss PJ. Compression behaviour of bridge bearings used for seismic isolation. Eng Struct 1996;18(5):351–62.
[2] Simo JC, Kelly JM. Finite element analysis of the stability of multilayer elastomeric bearings. Eng Struct 1984;6(3):162–74.
[3] Topkaya C. Analysis of specimen size effects in inclined compression test on laminated elastomeric bearings. Eng Struct 2004;26(8):1071–80.
[4] Kim SH, Mha HS, Lee SW. Effects of bearing damage upon seismic behaviors of a multi-span girder bridge. Eng Struct 2006;28(7):1071–80.
[5] Raheem ASE. Pounding mitigation and unseating prevention at expansion joints of isolated multi-span bridges. Eng Struct 2009;24(7):2345–56.
[6] Chang KC, Chang DW, Tsai MH, Sung YC. Seismic performance of highway bridges. Earthq Eng Eng Seismol 2000;2(1):55–77.
[7] Bruneau M, Wilson JW, Tremblay R. Performance of steel bridges during the 1995 Hyogo Ken Nanbu (Kobe Japan) earthquake. Can J Civ Eng 1996;23(3): 678–713.
[8] Jennings PC. Engineering features of the San Fernando earthquake of February 9, (1971). Report No. EERL-71-02. Pasadena: Earthquake Engineering Research Laboratory, California Institute of Technology.
[9] Moehle JP. Northridge earthquake of January 17, 1994: reconnaissance report, volume 1-highway bridges and traffic management. Earthq Spectra 1994; 11(3):287–372.
[10] Chaudhary MTA, Abe M, Fujino Y. Investigation of a typical seismic response of a base-isolated bridge. Eng Struct 2002;24(7):945–53.
[11] Padgett JE, DesRoches R. Three-dimensional nonlinear seismic performance evaluation of retrofit measures for typical steel girder bridges. Eng Struct 2008; 30(7):1869–78.
[12] Saiidi M, Maragakis EA, Feng S. An evaluation of the current Caltrans seismic restrainer design method. Report No. CCEER-92-8. Reno (NV): Civil Engineering Department, University of Nevada; (1992).
[13] Fenves G, DesRoches R. Response of the Northwest Connector in the Landers and Big Bear earthquakes. Report No. UCB/EERC-94/12. Berkeley (CA): University of California; 1994.
[14] Selena LG, Malvar LJ, Zelinski RJ. Bridge retrofit testing: hinge cable restrainers. J Struct Eng ASCE 1989;115(4):920–34.
[15] AASHTO. Standard specifications for highway bridges, 16th edition. Washington (DC): American Association of State Highway and Transportation Officials; 1996.
[16] CALTRANS. Memo to designers, 20–3, 20–4. Sacramento (CA): California Department of Transportation; 1994.
[17] CALTRANS. Seismic Design Criteria, 20–3, 20–4. Sacramento (CA): California Department of Transportation; 1999.
[18] Won JH, Mha HS, Cho KI, Kim SH. Effects of the restrainer upon bridge motions under seismic excitations. Eng Struct 2008;30(12):3532–44.
[19] Won JH, Mha HS, Cho II K, Kim SH. Effects of the restrainer upon bridge motions under seismic excitations. Eng Struct 2008;30(12):3532–44.
[20] Graesser EJ, Cozzarelli FA. Shape memory alloys as new materials for aseismic isolation. J Eng Mech, ASCE 1991;117(11):2590–608.
[21] Clark PW, Aiken ID, Kelly JM, Higashino M, Krumme RC. Experimental and analytical studies of shape memory alloy damper for structural control, In: Proceedings of passive damping. 1995.
[22] Bondonet G, Filiatrault A. Shape-memory alloys for seismic isolation of bridges. In: Proceedings of the eleventh world conference on earthquake engineering. 1996.
[23] Wilson JC, Wesolowsky MJ. Shape memory alloys for seismic response modification: a state-of-the-art review. Earthquake Spectra 2005;21(2): 569–601.
[24] Sharabash AM, Andrawes BO. Application of shape memory alloy dampers in the seismic control of cable-stayed bridges. Eng Struct 2009;31(2):607–16.
[25] Wilde K, Gardoni P, Fujino Y. Base isolation system with shape memory alloy device for elevated highway bridges. Eng Struct 2000;22(3):222–9.
[26] SAP2000. Integrated finite element analysis and design of structures. Comput Struct 2006.
[27] Thakkar SK, Zoravkovic S, Milutinovic Z, Petrovski J. Dynamic analysis of bridge system with restricted movements at supports. In: Seventh symposium on earthquake engineering, University of Roorkee, Nov. 10–12, 1. 1982. p. 299–302.
[28] DesRoches R, Andrawes B. Seismic retrofit of bridges using shape memory alloy restrainers. In: Proceedings of 3rd national seismic conference & workshop on bridges & highways. 2002. p. 43–52.
[29] DesRoches R, Delemont M. Seismic retrofit of simply supported bridges using shape memory alloys. Eng Struct 2002;24:325–32.
[30] Andrawes B, DesRoches R. Unseating prevention for multiple frame bridges using superelastic devices. Smart Mater Struct 2005;14:S60–7.
[31] Song G, Ma N, Li HN. Applications of shape memory alloys in civil structures. Eng Struct 2006;28(9):1266–74.
[32] Roh H, Reinhorn AM. Hysteretic behavior of precast segmental bridge piers with superelastic shape memory alloy bars. Eng Struct 2010;32(10):3394–403.
[33] Alam MS, Youssef MA, Nehdi M. Analytical prediction of the seismic behavior of superelastic shape memory alloy reinforced concrete elements. Eng Struct 2008;30(12):3399–411.
[34] IS: 1893-Part 1. Criteria for Earthquake Resistant Design of Structures-General Provisions and Buildings. New Delhi: Bureau of Indian Standards; 2002.
[35] Kumar A. Software for generation of spectrum compatible time history. In: Proceedings of 13th World Conference on Earthquake Engineering; 2004.
[36] IRC: 83 (Part II). Standard specifications and code of practice for road bridges-section IX-bearings (Part II): elastomeric bearings. New Delhi: The Indian Road Congress; 1987.
[37] AASHTO. Guide specifications for seismic isolation design. American Association of State Highway and Transportation Officials: Washington (DC); 1999.
[38] BS 5400. Steel, concrete and composite bridges: part 9, bridge bearings. London: British Standard Institution; 1993.