EFFECTIVENESS OF UNSEATING PREVENTION CABLE RESTRAINERS FOR ISOLATED CURVED BRIDGES UNDER NEAR-FAULT EARTHQUAKES

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ABSTRACT :

This paper examines the efficiency of cable restrainers to prevent unseating of curved bridges located at sites near active faults. Forward rupture-directivity effects associated to near-fault seismic ground motions have been responsible of catastrophic deck unseating and severe pounding damage at bridge expansion joints. Since destructive near-fault pulses are generally oriented perpendicular to the fault strike, a remarkable variability in damage level was observed depending on the orientation of bridge structures respect to the fault direction. Therefore, keeping in mind the above considerations, the as-recorded orthogonal horizontal components of two strong near-fault earthquakes have been rotated for each 15-degrees interval on the horizontal plane in order to simulate different orientations of the bridge respect to the fault. Following, a large number of three-dimensional nonlinear dynamic analyses have been performed to compare the effectiveness of various size cable restrainers to protect the bridge against seismic damage. Restrainers are bi-directionally modeled explicitly considering the possibility of yielding and failure of the cables under the high demands generated by near-fault motions. The investigation results provide sufficient evidences to conclude that, in accordance with considerable directivity of near-fault ground motions, bridge orientation with respect to the fault direction influence seismic damages and determine the protection efficiency exhibited by cable restrainers. Therefore, when it is not viable to revise road alignments to avoid a fault zone, acquisition of vital knowledge regarding to design of unseating restrainers becomes necessary for developing effective protection strategies applied to bridges located in the proximity of active faults.

KEYWORDS: Cable Restrainer, Curved Bridge, Near-Fault Earthquake, Deck Unseating

1. INTRODUCTION

In recent years, near-fault earthquakes have received increased recognition due to the devastating damages inflicted to critical facilities during the 1994 Northridge, 1995 Kobe and 1999 ChiChi earthquakes. Ground motions recorded within a few kilometers from the fault rupture are characterized by long period velocity pulses, large accelerations and permanent ground displacements. Furthermore, near-fault seismic excitations at a particular site are significantly influenced by rupture-directivity effects, particularly important in the forward direction of rupture propagation. Destructive pulses are typically aligned with the direction perpendicular to the fault strike, causing the strike-normal component of motion to be considerably larger than the strike-parallel component at long periods (Somerville 2003).

One of the most common causes of bridge collapse during those earthquakes was due to unseating of deck superstructures at expansion joints. This catastrophic failure occurs when the seismically induced relative displacement between the superstructure and its supporting substructure exceeds the available seat width, resulting in the loss of support at the joint. Bridges can be seismically protected through the installation of cable restrainers that limit relative movements between adjacent spans (DesRoches 2004). Post-earthquake evaluations from recent seismic events have shown that cable restrainers performed effectively to mitigate unseating during moderate-to-strong ground motions. However, the collapsed of restrained bridges due to unseating during the 1989 Loma Prieta and 1994 Northridge earthquakes proved that inadequate restrainer design can lead to catastrophic results.

Due to the expansion of highway systems to areas of high seismic risk, an increasing coincidence of near-fault earthquakes with bridge sites is expected. In spite of this fact, in many cases it is unfeasible to change the alignment of a roadway to avoid a fault area. For this reason, it is recognized of essential importance to improve the knowledge regarding to the dynamic behaviour of bridge structures subjected to near-fault earthquakes. It is evident that directionality characteristics of near-fault motions may determine the level of seismic demands experienced by cable restrainers. In the most critical case, when near-fault pulses are acting parallel to the axis of the cable, extremely high demands are expected. Regardless of this, the current seismic restrainer design methodologies (JRA 2002, Saiidi 2001), based exclusively on static analysis procedures, do not take into account the bridge response under earthquake loading. Therefore, there is significant uncertainty in how to properly design cable restrainers to resist the potential severity of near-fault motions. Although there has been an increase in research on the effects of near-fault motions on bridges, no research has been carried out regarding to the near-fault effects on restrained bridges.

The above considerations provide sufficient justification for focusing this study on the evaluation of the effectiveness of cable restrainers depending on the bridge orientation respect to the active fault. For this purpose, restrainers are bi-directionally modeled explicitly considering the possibility of yielding and failure of the cables in order to take into account the large deformations associated to near-fault motions. Then, a large number of nonlinear dynamic analyses have been carried out by rotating a three-dimensional model of bridge on the horizontal plane to simulate different orientations of the model respect to the fault. This bridge model includes various significant seismic hazards such as curved alignment, the presence of an expansion joint, and adjacent superstructures with different sizes as well as supported on different types of bearings. In a preliminary step, near-fault seismic demands on the unrestrained model have been calculated to obtain an accurate estimation of the most vulnerable bridge structural elements. Finally, the effectiveness of seismic cable restrainers to reduce critical structural responses has been investigated. Special emphasis is focused on the consequences of cable failure to increase the possibility of deck unseating and amplify the earthquake-induced pounding between adjacent superstructures at the expansion joint.

The results of this research attempt to provide an accurate quantification of the relation between directional dependence of near-fault motions and design of unseating prevention cable restrainers. The conclusions may help to develop effective retrofit strategies, enhancing the accuracy and reliability of the response of bridge structures to near-fault earthquakes.

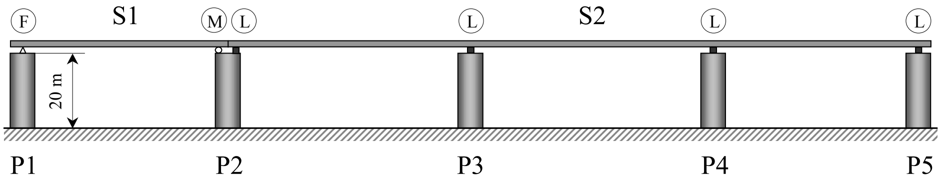
2. ANALYTICAL MODEL OF HIGHWAY VIADUCT

2.1. Superstructure and Piers

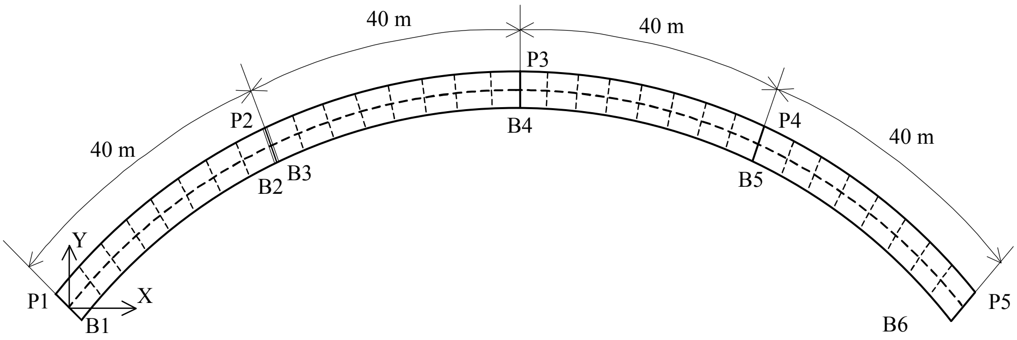
The highway viaduct considered in this study is composed by a single simply supported non-isolated span connected to a three-span continuous seismically isolated bridge section. Bridge alignment is horizontally curved in a circular arc with radius of curvature of 100 m. The total viaduct length of 160 m is divided in equal spans of 40 m, as represented in Fig. 1. The bridge superstructure consists of a concrete deck slab that rests on three I-shape steel girders, equally spaced at an interval of 2.1 m. The three girders (G1, G2 and G3) are interconnected by end-span diaphragms as well as intermediate diaphragms at uniform spacing of 5.0 m. Full composite action between the slab and the girders is assumed for the superstructure model, which is treated as a three-dimensional grillage beam system. The deck weight is sustained on the top of five hollow box section steel piers of 20 m height. Tangential configuration for both piers and bearing supports is adopted respect to the global coordinate system of the bridge.

2.2. Bearing Supports

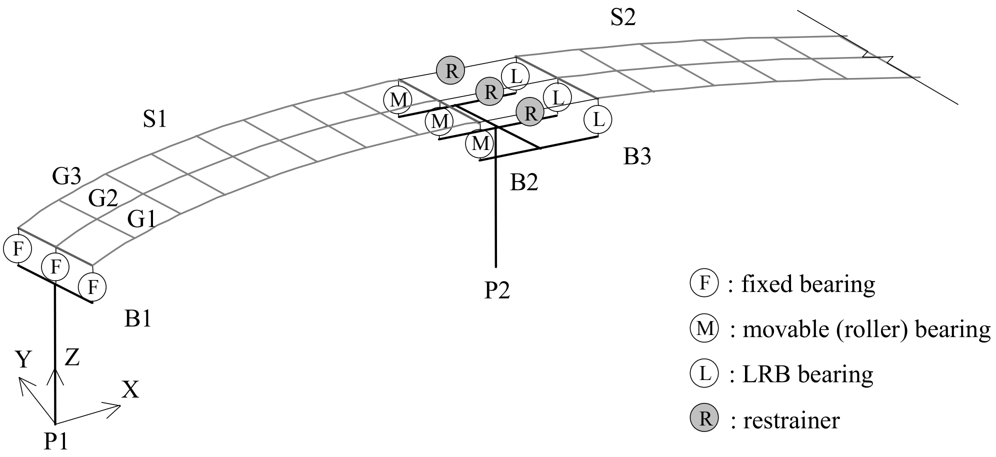
The non-isolated bridge section (S1) is supported by steel fixed and roller bearings. Coulomb friction force is taken into account for roller bearings, which allow movement tangent to the curved deck superstructure. The isolated continuous section (S2) is supported on top of four pier units (P2, P3, P4 and P5) by LRB bearings, which are modeled using bilinear force-displacement hysteretic loop. Structural characteristics of isolation bearings are obtained for a ratio of bearing yield force to the superstructure weight F_1/W_s of 10%. The pre-yield to post-yield stiffness ratio (K_1/K_2) is 10.0.



(a) Elevation view



(b) Plan view



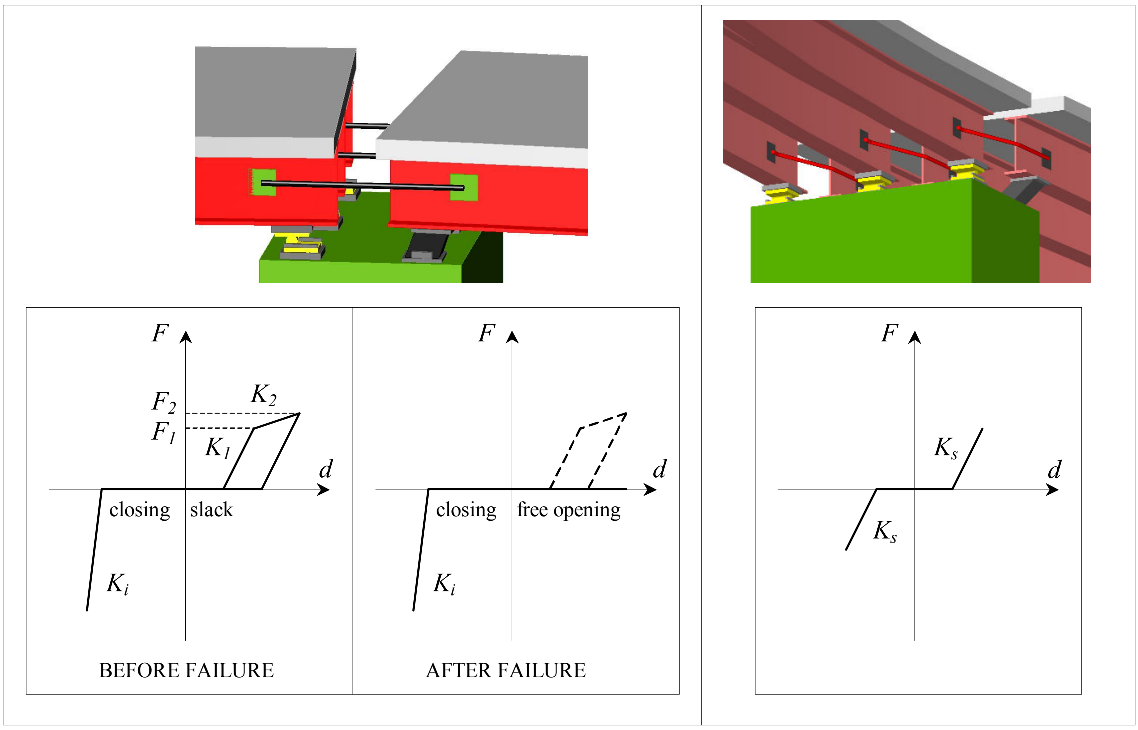
(c) Detail of finite element model

Figure 1 Analytical model of curved highway viaduct

Radial displacements of specific LRB bearings have been partially limited through the installation of lateral side stoppers. The solution to alleviate lateral forces without inducing excessive radial displacements consists in providing stoppers to end-span bearings in order to limit joint displacements exclusively in the in-plane tangential direction; while isolation units of intermediate piers are allowed for free displacements in both horizontal directions.

2.3. Expansion Joint

The isolated and non-isolated sections are separated, introducing a gap equal to the width of the expansion joint opening between adjacent spans. The joint allows for contraction and expansion of the road deck without generating constraint forces in the structure. In the event of strong earthquakes, the expansion joint gap of 0.1 m could close resulting in collision between the deck superstructures. Pounding phenomenon, defined as taking place at the three girder ends, is modeled using impact spring elements for which the compression-only bilinear gap element is provided with a spring of stiffness K_i = 980.0 MN/m that acts when the gap between the girders is completely closed.



(a) Tangential deformation (b) Radial deformation

Figure 2 Analytical model of cable restrainer

On the other hand, in order to limit excessive joint openings thus providing additional fail-safe protection against extreme seismic loads, three longitudinal cable restrainers are installed in the bridge model connecting adjacent superstructures along the expansion joint. The seismic cable restrainers, illustrated in Fig. 2, have been tangentially modeled as tension-only spring elements provided with a slack of 0.025 m, a value fitted to accommodate the expected deck thermal movements limiting the activation of the system specifically for earthquake loading. Initially, cable restrainers behave elastically with stiffness K_1, while their plasticity is introduced by the yield force (F_1) and the post-yielding stiffness ($K_2 = 0.05*K_1$). Finally, the failure statement is taken into account for ultimate strength F_2, and since then, adjacent spans can separate freely without any action of the unseating prevention device (Ruiz Julian 2007).

The viaduct seismic performance has been investigated for various restrainers of different sizes with structural properties based on the specified cross-sectional area (A), length (L) and modulus of elasticity of the cables (E), as summarized in Table 1. The expansion joint is constrained in the relative vertical movement while allows for both, tangential and radial, horizontal displacements. The unseating prevention device allows for movement radial to the bridge axis and the effect of restricted radial displacements due to the cable-girder interaction is considered by activation of a shear stiffness K_s = 49.0 MN/m once the gap of 0.05 m is exceeded. It is also pointed out that connection element of cable restrainers at the steel girders are assumed to be adequate, with deformations occurring exclusively for the cables. It is noted that the restrainer designation R0 indicates the unrestrained configuration for which no cables are installed in the viaduct model.

Table 1 Structural properties of cable restrainers

Cable Restrainer	E	A	L	K_1	K_2	F_1	F_2
	(GPa)	$\times 10^{-3}$ (m^2)	(m)	(MN/m)	(MN/m)	(MN)	(MN)
R130	200.0	0.691	1.110	124.505	6.225	1.092	1.283
R170	200.0	0.971	1.590	122.126	6.106	1.428	1.678
R210	200.0	1.042	1.590	131.069	6.553	1.649	1.938
R230	200.0	1.324	1.630	162.454	8.123	1.938	2.277

3. METHOD OF ANALYSIS

The analysis on the viaduct model is conducted using an analytical method based on the elasto-plastic finite displacement dynamic response analysis. The tangent stiffness matrix, considering both geometric and material nonlinearities, is adopted in this study, being the cross sectional properties of the nonlinear elements prescribed by using fiber elements. The stress-strain relation of the beam-column element is modeled as a bilinear type. The yield stress is 235.4 MPa, the elastic modulus is 200 GPa and the strain hardening in plastic area is 0.01. The implicit time integration Newmark scheme is formulated and used to directly calculate the responses. The Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations, while the damping of the structure is supposed as Rayleigh's type.
To evaluate the seismic performance of the viaduct, the nonlinear model is subjected to the simultaneous action of the longitudinal, transverse and vertical components of two different sets of ground motion inputs. The large magnitude seismic events used in this investigation, classified as near-fault earthquakes, are accelerograms obtained during the 1995 Kobe Earthquake at JR Takatori Station (TAK) and the 1999 Chi-Chi Earthquake at Station TCU 068 (CHI). Both seismic records are characterized by the presence of high peak accelerations and strong velocity pulses with a long period component as well as large ground displacements. These exceptionally powerful motions show directional characteristics typical of the ground motions recorded in the forward directivity region, for which the fault-normal component is much stronger than the fault-parallel component.

4. CALCULATED RESULTS

In order to asses the directivity effects of near-field motions on the performance of the restrainer system, the bridge principal axis alignment on the horizontal plane is rotated from 0 to 180 degrees at multiples of 15 degrees counterclockwise from the parallel to the fault direction. The input records are treated as vector quantities portioning them into the strike-normal and strike-parallel components transformed in the x- and y-directions of the bridge principal axes, as illustrated in Fig. 3.

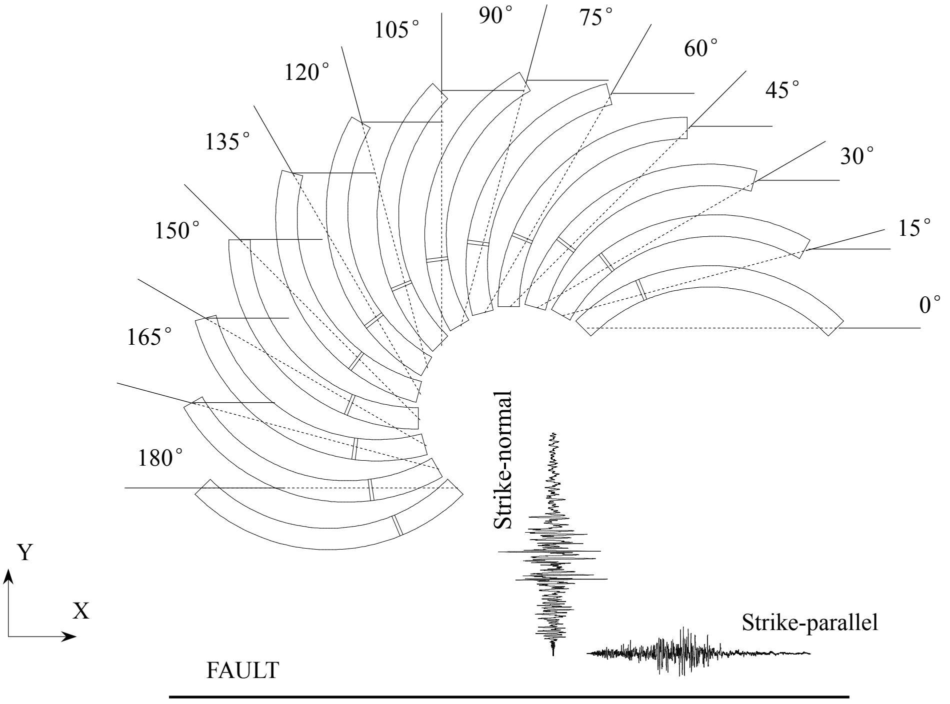
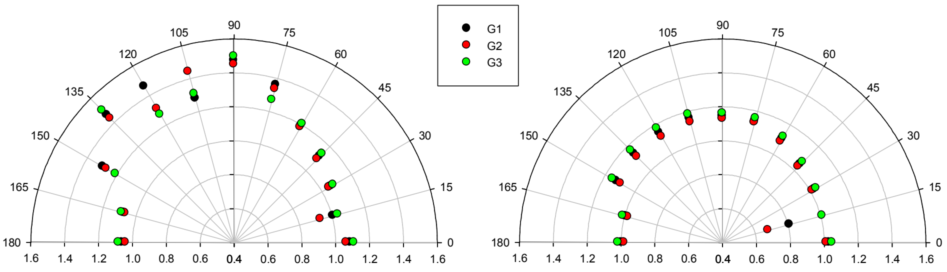
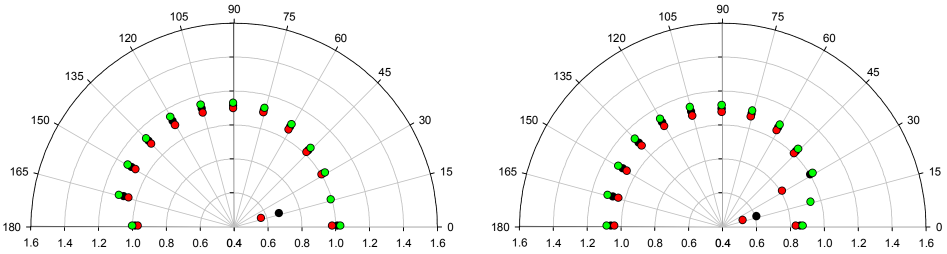


Figure 3 Study cases: bridge orientations respect to the fault strike

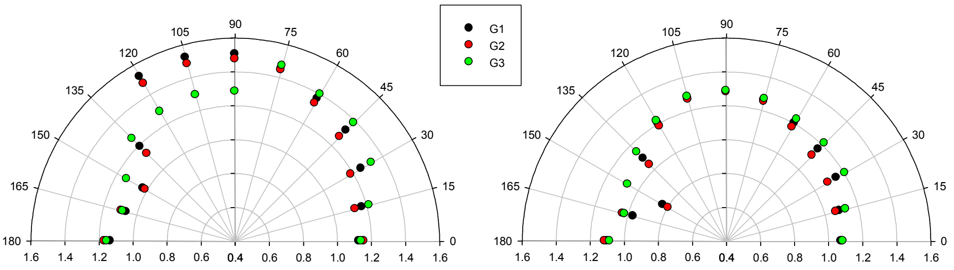


(a) R130 (b) R170

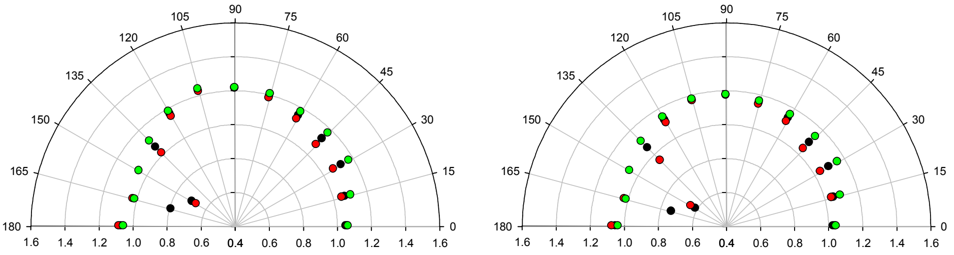


(c) R200 (d) R230

Figure 4 Evaluation of cable restrainer damage. MRSR (CHI)



(a) R130 (b) R170

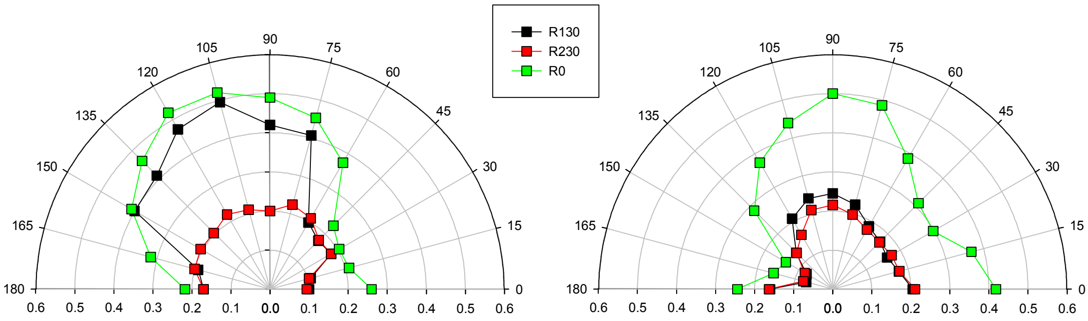


(c) R200 (d) R230

Figure 5 Evaluation of cable restrainer damage. MRSR (TAK)

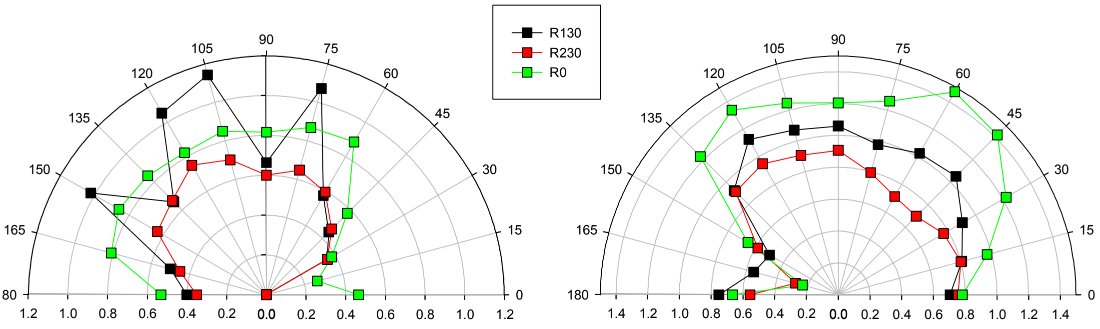
The analytical model of restrainer provides opportunity for investigating the failure possibility of the cable when subjected to the action of near-fault motions. The Maximum Restrainer Stress Ratio (MRSR) to the cable yield strength is established as the damage index. Cable restrainers reach their yielding state at MRSR value of 1.0, and have their ultimate strength at 1.175 times the MRSR. Maximum stresses of cables connecting the three girders (G1, G2 and G3) at the expansion joint are presented in Figs. 4 and 5. As expected, comparison of peak responses for the four restrainer cases confirms that magnitude of stresses decreases as the size of the cable is gradually increased. Restrainer yielding takes place in case of small-sized cables for which ductility demands are beyond the plastic strength of the cable. Moreover, it is particularly highlighted that failure of restrainers is found exclusively for a specific trend of orientations coincident with the fault normal direction. On the contrary, it is noticeable the absence of failure for the rest of orientations, for which restrainer stresses are well below the yield stress of the cables. It is additionally appreciated from the plots that the restrainer located at the exterior girder (G3) is generally subjected to the largest seismic demands. This results from the natural tendency of curved bridge configurations to increase the outer movements at the joint. Restrainers located at the exterior girder are first activated, thus exposed to larger earthquake loading, and consequently expected to be especially vulnerable to failure. The non-uniform distribution of maximum cable stresses results in a remarkable phenomenon observed when failure of the cables occurs exclusively in case of the exterior restrainer. This partial loss of functionality of the unseating prevention system is observed in several cases, for which spans are still connected at the expansion joint through the two remaining overloaded cable units.

Maximum Bearing (B2) Displacement (MB2D) responses in the negative tangential direction have been analyzed in order to evaluate the unseating potential possibility. Calculated results plotted in Fig. 6, present the shape of an elliptic lobe approximately in line with the perpendicular to the fault strike, corroborating the strong directionality of the records. Bridge orientations for which the structure rotation angle is radiating in the intervals 90-135 degrees (CHI); 75-105 degrees (TAK) lead to the highest unseating probability. These ranges of bridge orientation angles seem to indicate the critical cases when the opening direction of the joint is mainly affected by the strong shaking of the strike-normal near-fault component. As it can be observed from the plots, the installation of restrainers appears to be very effective in achieving essential reductions in the peak separations between adjacent bridge sections. It is noteworthy that, due to the effect of restrainers, the possibility of deck unseating is minimized, reducing the maximum relative displacements to values that do not exceed the standard seating length of bridge substructures. However, it is appreciated that failure of restrainers may eliminate the seismic protection to the bridge against unseating damage. In case of CHI input for orientations parallel to the fault, failure of small-sized restrainers takes place at the beginning of the record. Consequently, MB2D responses to subsequent pulses of motion are significantly higher with peak values similar to those obtained for the unrestrained model. In contrast, calculated results for TAK seismic motion are not substantially affected by failure of cables. Restrainers reach their ultimate strength at the end of the single strong seismic pulse after accomplishing their main function. Additionally, it is interesting to emphasize that size of cable restrainers do not significantly influence the unseating possibility for fault-parallel orientations. MB2D induced by weak parallel near-fault components are relatively small, hence cable restrainer effect is not as crucial as for fault-normal orientations.



(a) CHI (b) TAK

Figure 6 Evaluation of deck unseating damage. MB2D (m)



(a) CHI (b) TAK

Figure 7 Evaluation of pounding damage. RMIF

The Ratio of Maximum Impact Force (RMIF) to the deck weight has been established as estimation parameter of pounding damage. Peak responses of superstructure pounding, shown in Fig. 7, follows a similar trend as unseating evaluation results. Strong collisions between girders of adjacent spans are appreciated when the longitudinal axis of the expansion joint is nearly coincident to the parallel of the fault direction. In contrast, moderate pounding forces are found when opening/closing movements of the joint are affected by the weak strike-parallel components. Activation of cable restrainers results in significant reductions of joint impact forces. This is due to the fact that restrainers tend to uniform the relative velocities of colliding sections at the moment of the impact in such way that maximum pounding forces can be effectively reduced [Ruiz Julian 2005]. Nevertheless, detrimental effect due to failure of cable restrainers can be observed in case of CHI input record. In several failure cases, pounding peak responses reach higher values than those obtained for the unrestrained model. Theses results are significative, demonstrating the damaging consequences that deficient design of the unseating prevention system may provoke on seismic responses of bridge structures.

5. CONCLUSIONS

This study introduces the directional effects of near-fault earthquakes on the three-dimensional nonlinear response of restrained curved bridges. Conclusions are summarized as follows:

1. Calculated results clearly demonstrate the correlation between structural damage and bridge orientation respect to the fault. It is concluded that the possibility of superstructure unseating is substantially higher when the expansion joint axis is almost parallel to the strike of the fault. Directional effects, typical of near-fault motions, are also responsible of considerable increase of pounding damage at expansion joints.
2. Cable restrainers are effective to improve the seismic protection of bridge structures located near active faults. Restrainers greatly reduce critical seismic responses for those orientations for which expansion joint movements are severely affected by near-fault pulses. Moreover, bi-directional performance of restrainers allows for decreasing seismic damages for the rest of bridge orientations.
3. Failure of insufficient-sized cable restrainers is found for specific bridge orientations affected by strike-normal components of near-fault motions. Required attention should be paid to failure of cables since detrimental effects on bridge responses are observed. Therefore, accurate nonlinear modeling strategies of cable restrainers become necessary in order to correctly simulate the behaviour of such systems under the action of near-fault earthquakes.
4. In order to provide consistent protection to bridges located in near-fault regions, careful consideration should be given to the design of unseating prevention cable restrainers. Since the restrainer system performance is highly dependent on the bridge orientation respect to the fault in case of near-fault motions, special precautions should be taken for an accurate estimation of the optimal size of the cable.

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