Critical Performance of Unseating Prevention Cable Restrainers Under Level II Earthquakes

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1. INTRODUCTION

Recent strong earthquakes have repeatedly demonstrated that one of the primary causes of bridge collapse during earthquakes is due to unseating of deck superstructures at the expansion joints[1)]. This catastrophic result occurs when the seismically induced relative displacement between the deck and the supporting substructure exceeds the available seat width. As a result of the implementation of modern seismic protection technologies, bridges can be seismically upgraded through the installation of cable restrainers that provide connection between adjacent spans. This type of unseating prevention system is established in addition to the seating width to provide a fail-safe function against unexpected great seismic forces by limiting the relative movements of bridge superstructures and thus, minimizing the possibility of support loss at expansion joints[2)].

Post-earthquake evaluations from recent seismic events have shown that many cable restrainers performed effectively during the earthquakes, preventing simply-supported spans from falling from their supports[3)]. However, the collapse of the Gavin Canyon undercrossing during the 1994 Northridge earthquake proved that inadequate restrainer design can have catastrophic results[4)]. The current seismic restrainer design methodology[5, 6)], based static analysis procedures, is not able to ensure the ability of restrainers to operate under the high demands generated by Level II earthquake ground motions. Moreover, while the effects of cable restrainers are well understood for straight bridges, it is not clear how effective this unseating prevention measure is for curved bridges. This fact is caused by the considerable complexity associated with seismically induced joint movements in curved bridges, which may occur in both tangential and radial directions.

Therefore, this paper presents an in-depth analysis on the seismic performance of cable restrainers installed in a substantially adverse case of highway viaduct configuration, which concentrates various significant seismic hazards, including curved deck alignment, the presence of an expansion joint, and adjacent bridge sections with different sizes and bearing supports. The study combines the use of non-linear dynamic analysis with a three-dimensional non-linear bridge model to accurately evaluate the seismic demands on various different sizes of cable restrainers in the event of severe earthquakes. In order to perform a complete investigation an innovative model of cable restrainers, which takes into account their bi-directional behaviour as well as the yielding and failure statements of the cables, is presented.

2. ANALYTICAL MODEL OF HIGHWAY VIADUCT

The highway viaduct considered in this study is composed by a three-span continuous seismically isolated bridge section connected to a single simply supported non-isolated span. The 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 deck superstructure model, which is treated as the three-dimensional grillage beam system presented in **Fig. 2**. 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.

The non-isolated simply supported bridge section (S1) is supported by steel fixed (**Fig. 3** (a)) and steel roller (**Fig. 3** (b)) bearings. Coulomb friction force is taken into account for the 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 represented by the bilinear force-displacement hysteresis loop given in **Fig. 3** (c). The seismic performance of the viaduct has been evaluated for three different LRB bearing supports: soft (L1), medium (L2) and stiff (L3). Structural characteristics of isolation bearings are obtained by varying the size of the lead plug or equivalently modifying the ratio of bearing yield force to the superstructure weight F_1/W_S (5%, 10%, and 15% for L1, L2 and L3 bearings, respectively). The pre-yield to post-yield stiffness ratio is kept constant for the three types of LRB bearings at K_1/K_2 = 10.0.

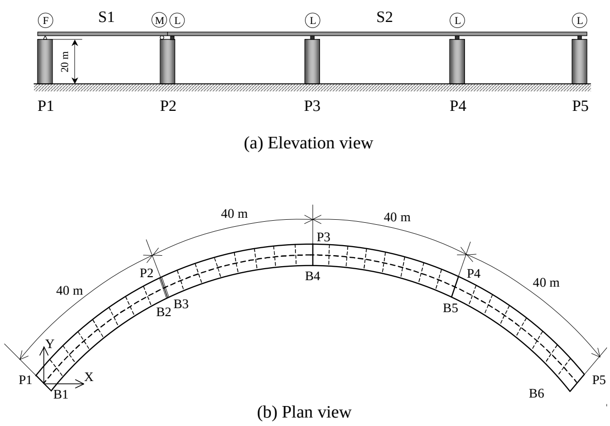


Fig. 1 Model of curved highway viaduct

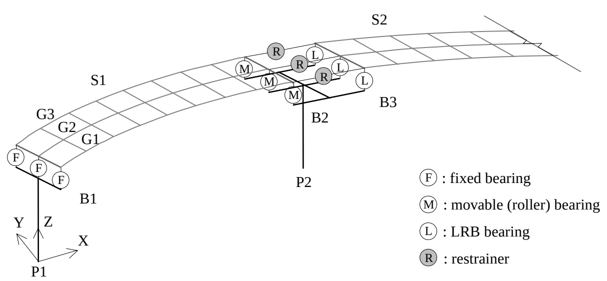


Fig. 2 Detail of curved viaduct finite element model

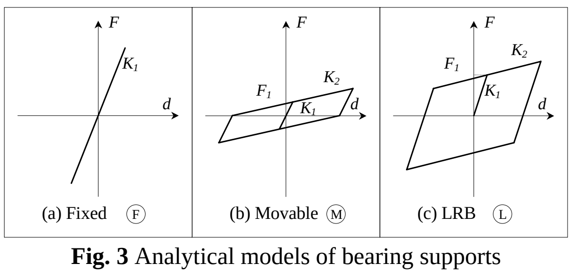


Fig. 3 Analytical models of bearing supports

Radial displacements of LRB bearings have been partially limited for some configurations through the installation of lateral side stoppers, as shown graphically in **Fig. 4**. Out-plane radial displacements are restricted in a-configuration for all isolation units, representing the most commonly used method of bearing restraint in Japan. LRB bearings in b-configuration are such as to allow for free horizontal movements. This is the simplest bearing arrangement, which has the advantage to distribute horizontal forces in both bridge horizontal directions. This fact also makes the structure susceptible to large radial displacements that may develop when the bridge is subjected to strong earthquake loading. Finally, an intermediate solution is adopted for c-configuration to alleviate the lateral forces without inducing excessive radial displacements. The modification consists in providing stoppers to end-span bearings to limit the joint displacements exclusively in the in-plane tangential direction; while the bearings of intermediate piers are free two move in both directions.

The isolated and non-isolated sections of the viaduct are separated, introducing a gap equal to the width of the expansion joint opening between adjacent spans, to allow for contraction and expansion of the road deck from creep, shrinkage, temperature fluctuations and traffic 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 modelled 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.

On the other hand, in order to limit the excessive opening of the expansion joint gap thus providing additional fail-safe protection against extreme seismic loads, three longitudinal cable restrainers are installed in the bridge model connecting the two adjacent superstructures along the expansion joint. The seismic cable restrainers, illustrated in **Fig. 5**, 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, 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. The viaduct seismic performance has been investigated for several 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. According to examples of past disasters, many cases of seismic damage have been observed that accompanied displacement radial to the bridge axis, and some seem to have resulted from the impact of a seismic force in the unseating prevention structure. Accordingly, the unseating prevention structures allows 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 elements of cable restrainers at the steel girders are assumed to be adequate, with deformations occurring exclusively for the cables.

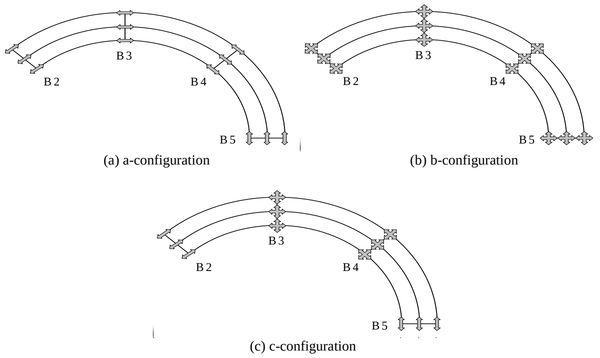
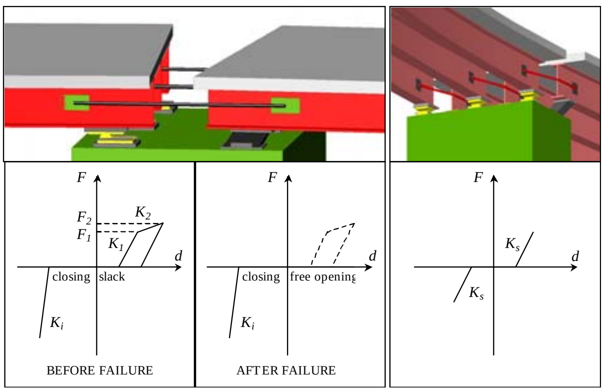


Fig. 4 LRB bearing configurations of S2



(a) tangential deformation (b) radial deformation

Fig. 5 Analytical model of cable restrainer

3. METHOD OF ANALYSIS

The analysis on the highway 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 relationship 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, while the Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations. The damping of the structure is supposed a Rayleigh's type, assuming a damping coefficient of the first two natural modes of 2%.

Table 1 Structural properties of cable restrainers

Cable restrainer	E (GPa)	A $*10^{-3}$ (m^2)	L (m)	K_1 (MN/m)	K_2 (MN/m)	F_1 (MN)	F_2 (MN)
R1	200.0	1.042	1.590	131.069	6.553	1.649	1.938
R2	200.0	1.324	1.630	162.442	8.122	1.938	2.280
R3	200.0	1.410	1.670	168.814	8.441	2.242	2.622
R4	200.0	1.765	1.730	204.058	10.203	2.584	3.040
R5	200.0	1.876	1.750	214.343	10.717	2.964	3.477
R6	200.0	2.635	3.360	156.863	7.843	4.178	4.761

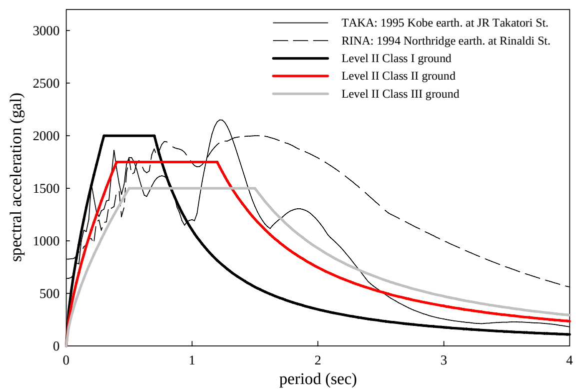


Fig. 6 Acceleration response spectra for input records

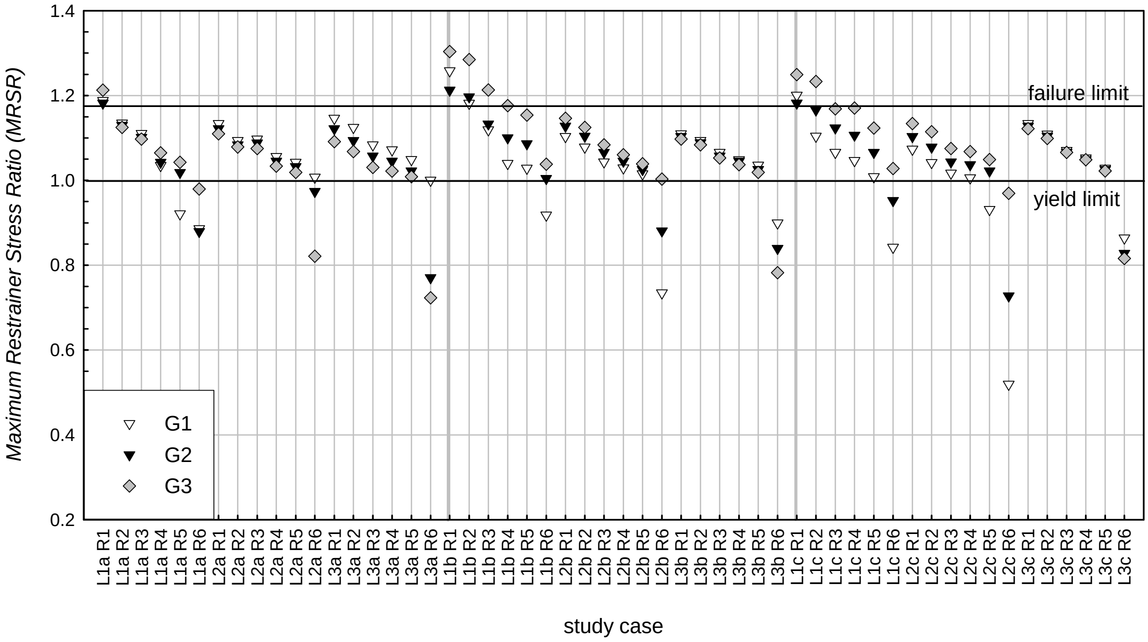


Fig. 7 Evaluation of cable restrainer performance under TAKA earthquake

To assess the seismic performance of the viaduct, the nonlinear bridge model is subjected to the longitudinal (L), transverse (T) and vertical (V) components of two different sets of seismic ground motion inputs. **Fig. 6** shows the acceleration response spectra of the strongest directions for the suites of earthquakes used in this investigation, calculated at a damping ratio of 5%. The large magnitude events used in this investigation, classified as Level II ground motions, are accelerograms obtained from the 1994 Northridge and the 1995 Hyogoken Nanbu earthquakes. 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 strong motions have been selected due to the destructive potential of long duration pulses on structures equipped with isolation systems that can lead to large isolator displacements, probably exciting the bridge into its nonlinear range as well as inducing opening and pounding phenomenon at the expansion joint.

4. NUMERICAL RESULTS

For an easy identification of the different study cases, a specific nomenclature is adopted in this investigation. The first part (L) refers to the LRB bearing characteristics: stiffness of the isolator and radial restraint configuration; the second part (R) indicates the size of the cables that connect the adjacent girders at the joint. As an example, L2bR3 corresponds to the case of stiffness type 2 LRB bearings in b-configuration with cable restrainer size classified as R3 in **Table 1**. It is also noted that the restrainer designation R0 indicates that no cables are installed in the viaduct model.

In the current Japanese Specifications[5)], the minimum horizontal restrainer force between adjacent superstructures is prescribed to be 1.5 times the reaction force for the dead load of the superstructure. Therefore, the evaluation of restrainer capacity is based exclusively on static analysis, and the method does not take into account for the dynamic bridge response under the action of earthquake loading. Without this information, it is sensibly complicated to ensure an adequate proportioning of selected restrainers to resist the large seismic demands from near-fault earthquakes. The premature failure of restrainers is of primary concern because it may expose the bridge to deck unseating during the same earthquake shaking or future aftershocks. For this reason, cable restrainers have been modeled to adequately capture their non-linear complex behaviour, including simulation of yielding and failure of cables. The maximum restrainer stress ratio (*MRSR*) to the yield stress is established as the damage index. Cable restrainers yield for values of *MRSR* above 1.0, having their ultimate strength at 1.175 times the *MRSR*. Maximum stresses acting on restrainers located at the three girders (G1, G2 and G3) are presented for the two earthquake loadings considered in this study in **Figs. 7** and **8**.

The peak cable responses indicate the general trend that magnitude of restrainer stresses generally decreases as the size of the cable is increased. As expected, restrainer yielding and failure occur for small size cables for which ductility demands are beyond the available design stress of the cable. Consequently, it is noticeable the absence of failure for large size restrainers, which present peak restrainer stresses well below the yield stress for all cases. It is particularly important to note that both Level II earthquakes are able to induce plastic demands on cable restrainers for most of the analyzed cases. Furthermore, elastic behaviour of the cables is ensured uniquely for those cases in which cables of the largest size (R6) connect the adjacent bridge sections.

A detailed examination of the calculated results have revealed the fact that failure of restrainers is found exclusively for viaducts supported on soft LRB bearings (L1). Breakage of cables takes place for six cases under TAKA input wave (L1aR1, L1bR1, L1bR2, L1bR3, L1cR1, and L1cR2); and for a single case when subjected to RINA seismic record (L1cR1). Therefore, these results confirm that the increase of flexibility by introducing soft isolation bearings results in large relative displacements at the expansion joint, which tangibly magnify the seismic demands to cable restrainers.

It is important to clarify at this point that the restrainer located at the exterior girder (G3) is generally subjected to the largest earthquake demands. This discrepancy in loads results from the natural tendency of bridge structures with curved configurations to increase the external side movement at the expansion joint. Consequently, the restrainer located at the exterior girder is first activated, thus subjected to larger seismic forces, and consequently expected to be particularly vulnerable to failure.

Additionally, the non-uniform distribution of maximum cable stresses results in a curious phenomenon when failure of the cables occurs only for the exterior restrainer. This partial loss of function of the unseating prevention system is observed

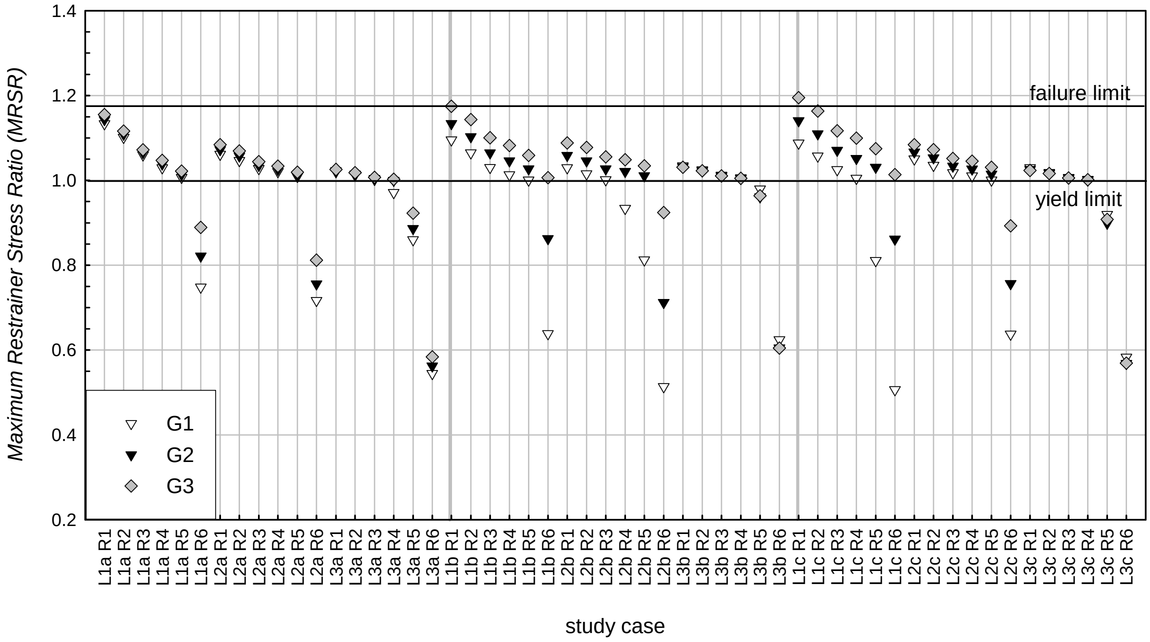


Fig. 8 Evaluation of cable restrainer performance under RINA earthquake

in three cases (L1bR3 and L1cR2 for TAKA input, and L1cR1 for RINA record), for which the bridge spans are still connected at the expansion joint through the two remaining overloaded cable units.

It is finally appreciated that stiffer restrainers present a more uniform load distribution among the three cables than the less stiff restrainers that have large load concentrations at the exterior restrainer unit. Regarding to the isolator radial restraint effects, it is clear that a-configuration, which allows exclusively for tangential movements of the isolated section, results in the most uniform and low demands for cable restrainers. On the contrary, it is relevant the fact that radially unrestrained flexible LRB bearings in b- and c- configurations tend to increase the difference of earthquake demands acting on different cable restrainers, depending on their position along the expansion joint.

5. CONCLUSIONS

An extensive performance evaluation of seismic unseating prevention cable restrainers under the action of Level II earthquake ground motions has been carried out through three-dimensional nonlinear finite element response analysis. The investigation results provide sufficient evidence for the following conclusions:

1) It is concluded in this study that cable restrainers, subjected to the extreme demands of Level II earthquakes, substantially exceed their demand capacities. As a consequence of this fact, ignored by the current design procedures, the viaduct seismic damage may be increased by the failure of cables. For this reason, in order to prevent collapse and ensure the post-earthquake serviceability of important bridges during strong seismic events, simulation of restrainer behaviour requires a sophisticated analytical model, which includes yielding and failure statements of the cable. Additionally, the evaluation of seismic performance of viaducts equipped with cable restrainers should be designed considering the bridge non-linear dynamic response.
2) It is additionally highlighted that cable restrainers are particularly vulnerable to failure when the viaduct is supported on excessively flexible LRB isolation bearings. Moderately stiff LRB bearings perform superior as compared to flexible bearings, which can substantially increase seismic demands on the cables, particularly when the isolation bearings located under the expansion joint are free to move in both horizontal directions. Therefore, the design of deck unseating prevention systems should be performed taking into account the characteristics of the isolation system installed in the highway viaduct.
3) The precise three-dimensional viaduct model proposed in this study allows for evaluation of the individual restrainer seismic response. The calculated results reveal that the presence of the curved deck geometry induces an irregular distribution of restrainer stresses depending on their position along the expansion joint. It is observed that the restrainer located at the exterior girder is first activated, thus subjected to the largest seismic demands, and consequently expected to be specially vulnerable to seismic failure.

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