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Effect of Restrainers on 3-Dimensional Nonlinear Seismic Response of Multi-Span Simply Supported Skewed Highway Viaducts

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1. INTRODUCTION

In the last years there has been a steady increase in the use of skewed viaducts at highway interchanges and urban areas due primarily to the need to expand the traffic capacities, seriously limited by lack of space in existing land. Bridges with skewed geometry are also commonly adopted at river crossings in order to preserve the continuity of the road.

Bridges have traditionally been designed exclusively for movement in the longitudinal direction. The presence of skewed configurations may result in coupled translational-rotational bridge displacements which greatly increase their susceptibility to be damaged during strong earthquakes. For this reason, bridges with skewed decks have shown to be specially vulnerable to seismic loads, and severe damages to piers and abutments have been observed in recent large earthquakes[1)].

On the other hand, in order to accommodate movements due to temperature variations without inducing large forces in the bridge, spans need to be separated with expansion joints. Earthquake-induced span separation of multisimple-span bridges is commonly recognized as hazardous to the overall stability of the structure[2)]. Differences in vibration properties of spans and non-uniform ground excitations at the bridge supports may cause large differential movements of the adjacent spans of the bridge during a strong ground shaking[3)]. If the relative displacement of adjacent spans exceeds the available seat width, the span will collapse. In addition, pounding of adjacent superstructures can result in significant structural damage[4)]. Impact forces may cause severe local damage to bearing supports, girder ends and abutment back walls. The collisions can be avoided by enlarging the gap size between decks. However, it results in an expensive and undesirable solution, because the adoption of large expansion joints increases traveling, maintenance, noise and vibration problems to the bridge[5)].

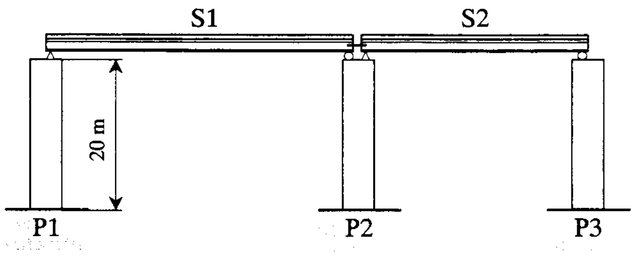
The objective of this study is, combining together the two seismic hazards previously described, to analyze the overall behaviour of multi-span simply supported highway viaducts with skewed configurations subjected to great earthquake ground motions. In addition, the effectiveness of cable restrainers to reduce the seismic structural responses has been investigated with special emphasis focused on the three-dimensional seismic behaviour of the viaduct including the effects of pounding between adjacent superstructure elements of the bridge.

2. ANALYTICAL MODEL OF HIGHWAY VIADUCT

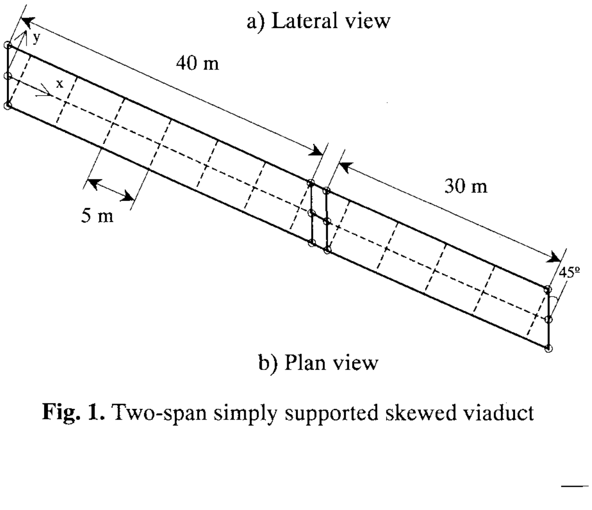
The highway viaduct considered in the analysis is a two-span simply supported bridge having an overall span length of 70 m divided in two spans of 40 and 30 m, as it is presented in **Fig. 1**.

The superstructure is composed of a concrete deck slab supported on three I-shape steel girders equally spaced at 2.1 m. The girders are interconnected by end-span diaphragms as well as intermediate diaphragms at an uniform spacing of 5 m. Full composite action between the slab and the steel girders is assumed for the superstructure model which is treated as a three-dimensional grillage beam system (**Fig. 2**). The bridge deck is assumed to be skewed at angle 45º in the longitudinal direction. Therefore, the three hollow box section steel piers of 20 m height have been oriented at 45-degree skew from a line perpendicular to a straight bridge centerline alignment.

Fixed bearings (**Fig. 3-a**) are installed across the full width on the left end of the left span (S1), resting on the Pier 1 (P1). At the right end, on the Pier 2 (P2), roller bearings (**Fig. 3-b**), allow for expansion in the longitudinal direction only. The right span (S2) is supported at the left end by fixed bearings resting on the same P2 which supports S1 and at the other end by roller bearings on the top of Pier 3 (P3).



a) Lateral view



b) Plan view

Fig. 1. Two-span simply supported skewed viaduct

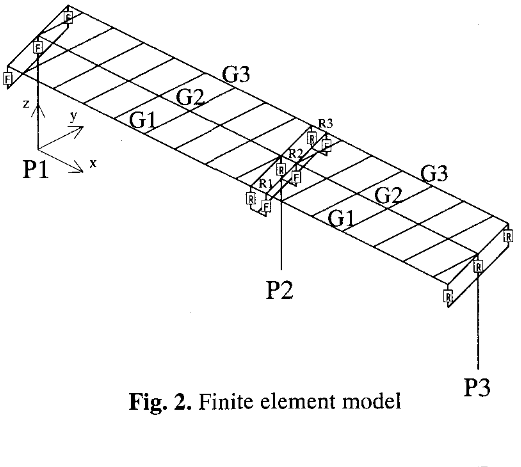
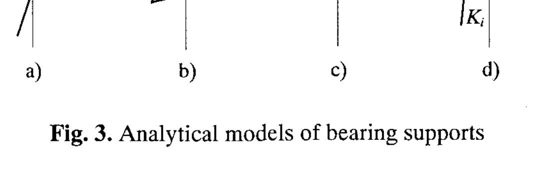


Fig. 2. Finite element model



a)　b)　c)　d)

Fig. 3. Analytical models of bearing supports

Three cable restrainers (R1, R2 and R3) are installed in the bridge model connecting the three girders (G1, G2 and G3) of S1 and S2, along the expansion joint over the P2. The seismic restrainers are modeled as tension-only spring elements (**Fig. 3-c**) provided with a slack of 0.025 m to limit their activation during thermal cycles. The seismic performance of the bridge is evaluated for three different values of restrainer stiffness (K_r=9.8, 49.0, and 98.0 MN/m). The two simply supported spans are separated, introducing a gap equal to the width of the expansion joint opening between the adjacent spans. In an extreme activity this gap, assumed to be 0.125 m, could close and the decks impact each other. This pounding phenomenon is modeled using an impact spring element represented in **Fig. 3-d**. The compression-only bilinear gap element has a spring of stiffness K_i = 980 MN/m that penalize closing the gap.

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, with a damping coefficient of the first two natural modes of 2%.

4. NONLINEAR DYNAMIC RESPONSE

The dynamic characteristics of the highway viaduct have been previously calculated through natural vibration analysis. The fundamental natural period, 0.715 sec, corresponds to the modal vibration in the transverse direction of the structure. While the second mode involves the longitudinal translation of the bridge with a period of vibration of 0.640 sec.

The nonlinear model is subjected to the longitudinal (L), transverse (T) and vertical (V) components of three different sets of strong ground motion records given in **Table 1**.

Force and displacement-time histories at every bearing support are calculated for both, longitudinal and transverse, directions. From the obtained results, one of the important points to consider is that, for bearings of the same pier, those located at the bridge centerline are observed to attract smaller seismic forces than the others. The maximum bearing forces generally occur at the exterior girder G1 for the left span S1, and at the exterior girder G3 in case of the right span S2. This is caused by the natural tendency of skewed bridges to rotate with respect to the vertical axis, resulting in significant unbalanced distribution of bearing reaction forces, specially in the transverse direction, as it can be observed in **Fig. 4**.

Table 1. Input earthquake ground motions

Earthquake		a_{max} (gal)	v_{max} (kine)	d_{max} (cm)	T (sec)
JR Takatori	L	641.7	120.4	31.9	1.241
	T	666.2	89.1	26.5	1.170
	V	289.7	16.3	4.4	0.125
Rinaldi	L	826.0	172.6	48.7	1.365
	T	471.0	79.5	50.5	0.301
	V	830.0	41.5	51.1	0.126
Sylmar	L	593.0	77.8	20.3	0.862
	T	827.0	128.8	30.6	1.575
	V	525.0	19.3	13.2	0.773

This differential behaviour across the width of the deck is also appreciated for the maximum impact forces calculated at the expansion joint, as shown in **Fig. 5**. In case of JR Takatori input wave pounding occurs once during the earthquake excitation, adjacent spans collide twice for Rinaldi record, and there are no collisions observed for the Sylmar seismic input. Summarized in **Table 2**, impact force values are found to vary considerably depending on the earthquake excitation as well as with the girder location. The significant differences in percentages of the total impact force absorbed by each one of the girders, clearly indicate the unbalanced situation created by the skewness of the deck.

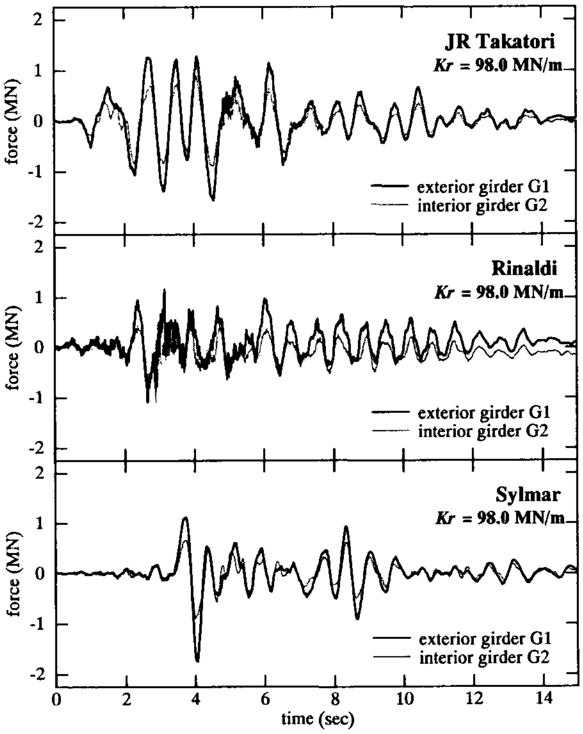


Fig. 4. Transverse seismic response at fixed bearings of P1

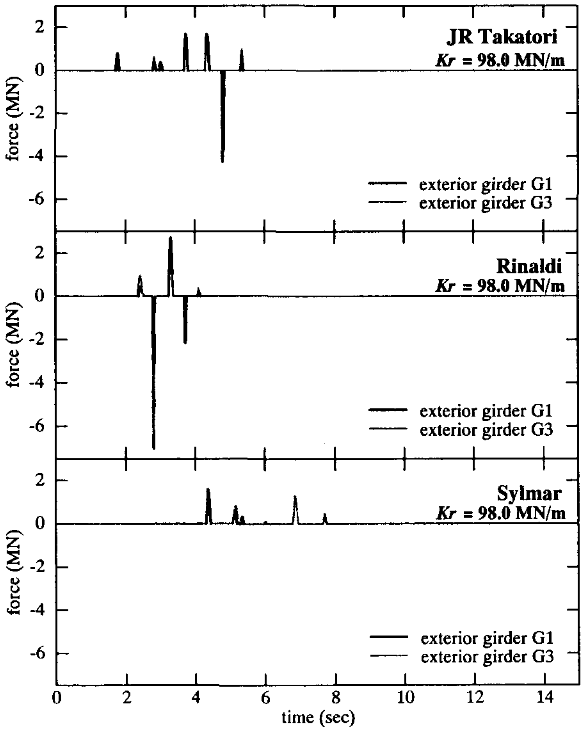


Fig. 5. Seismic response at expansion joint

Table 2. Maximum impact forces (MN)

Restrainer stiffness/location		Input earthquake wave		
		JR Takatori	Rinaldi	Sylmar
K_r = 0.0 MN/m	G1	2.50 (32.5%)	7.52 (35.1%)	0.00
	G2	2.44 (31.7%)	6.83 (31.9%)	0.00
	G3	2.75 (35.8%)	7.06 (33.0%)	0.00
K_r = 9.8 MN/m	G1	3.02 (38.5%)	7.20 (35.7%)	0.00
	G2	2.47 (31.5%)	6.42 (31.8%)	0.00
	G3	2.36 (30.0%)	6.57 (32.5%)	0.00
K_r = 49.0 MN/m	G1	**3.66 (46.3%)**	6.97 (36.4%)	0.00
	G2	2.56 (32.4%)	6.06 (31.6%)	0.00
	G3	**1.68 (21.3%)**	6.12 (32.0%)	0.00
K_r = 98.0 MN/m	G1	**4.25 (49.4%)**	7.01 (35.5%)	0.00
	G2	2.78 (32.2%)	6.26 (31.7%)	0.00
	G3	**1.59 (18.4%)**	6.49 (32.8%)	0.00

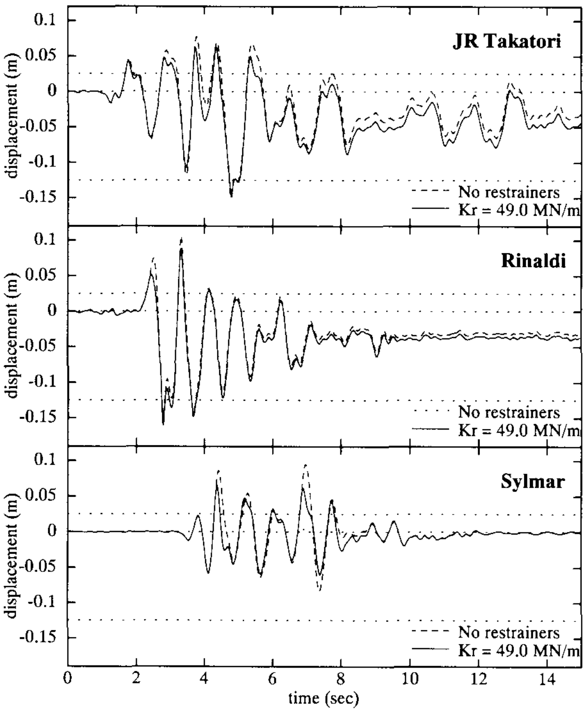


Fig. 6. Relative displacement between adjacent spans

Impacts are transmitted to the bearing supports of P2 in form of large spikes in both components of reaction forces. As these impact forces are not uniform across the expansion joint, the bearings supporting girders affected by larger collisions will attract more amount of transmitted forces. Consequently, these bearings will become specially vulnerable to failure due to breakage of the anchor bolts which attach the bearing to the superstructure, increasing the possibility of deck unseating with catastrophic consequences for the stability of the bridge in the event of great earthquakes.

The calculated results also indicate that cable-restrainers provided to link the spans are not effective in mitigating pounding forces. It is seen that the unbalanced distribution of impacts tends to increase with the stiffness of restrainers, specially for the JR Takatori input earthquake. This is due to the fact that before the main impact occurs, restrainers have been already activated in order to avoid large separations of adjacent spans. These restrainers are subjected to different tension demands depending on their position due to the skewed bridge configuration. Consequently, when the girders collide each other, the impact force values are observed to be significantly different.

On the other hand, as it is clearly observed in **Fig. 6**, restrainers appear to be quite effective in achieving significant reductions in the maximum separation between adjacent spans at the expansion joint. Restrainers assure reductions up to 30%, 35% and 43% in the maximum relative opening displacements for JR Takatori, Rinaldi and Sylmar input ground motions, respectively.

In **Fig. 7**, the maximum bearing displacements of roller bearings are presented. The calculated results indicate that restrainers simultaneously reduce the maximum displacement of the roller bearings of P2, increasing the peak displacement for bearings of P3. The restrainers act as a link between both decks, decreasing the possibility of unseating of S1 at P2. However, the opposite effect takes place for S2 and the increased maximum displacements of roller bearings of P3 could exceed the seating length of the pier, specially in case of Rinaldi input ground motion.

The ratios of maximum to the yield bending moment at the base of piers P1 and P2, for the longitudinal and transverse directions, are shown in **Fig. 8**. Calculated ductility demands of P3 are comparatively smaller because this pier is provided with roller bearings, and in order to simplify the plots have been omitted in this paper. Values of maximum longitudinal bending moments of P1 are generally larger than those for P2, because most critical seismic forces are transmitted to the fixed bearings of P1. This pier clearly exceeds its elastic range for JR Takatori and Rinaldi input waves. In the transverse direction, due to the effect of the skewed configuration of the highway viaduct, large ductility demands are observed for both piers and for all earthquake loadings considered in this study.

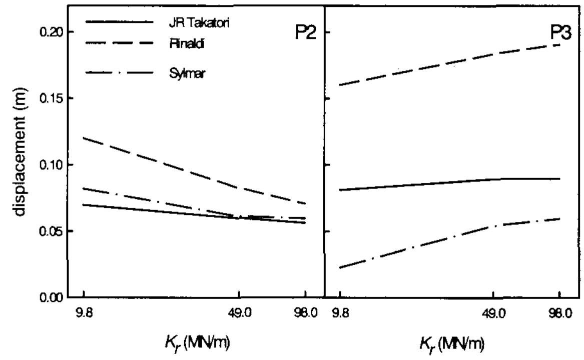


Fig. 7. Maximum displacements of roller bearing supports

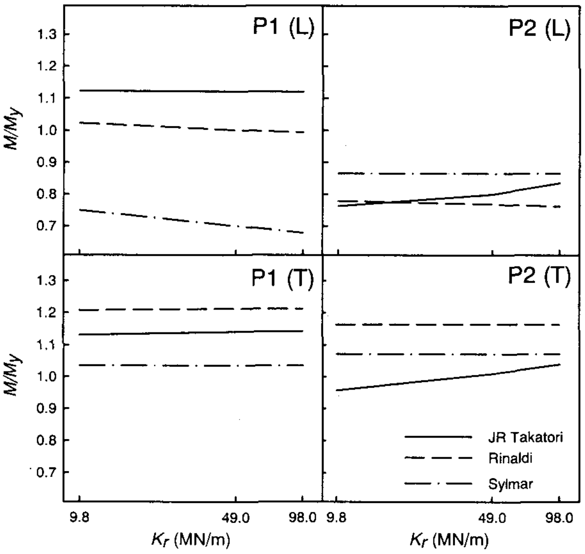


Fig. 8. Maximum bending moment response at base of piers

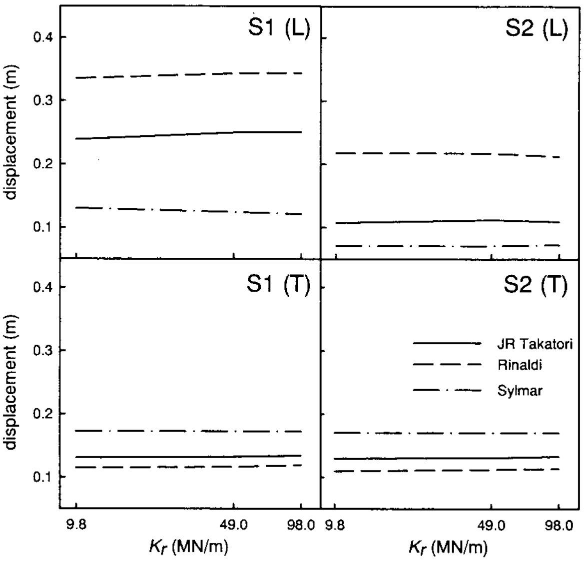


Fig. 9. Maximum deck displacement response

In general, the presence of restrainers does not significantly alter the seismic response of the bridge piers. Only in case of JR Takatori input earthquake, it is seen that restrainers increase the maximum bending moments of P2 because, as previously explained, the transmitted impact forces to the pier through the bearing supports are increased with the stiffness of the restrainers.

Cable restrainers do not dissipate any significant amount of energy since they are designed to remain elastic. Consequently, there is only a transference of seismic forces between adjacent piers as the gap opening exceeds the slack in the cable restrainer. The global damage to the substructure elements is similar in case of restrainers are installed or not. However, special care should be taken in seismic retrofitting because, with the adoption of restrainers, the induced forces transmitted to the piers could be different to those originally assumed in design, and they may modify the expected bridge seismic behaviour.

The calculated absolute maximum displacements of deck superstructures, plotted in **Fig. 9**, indicate that longitudinal deck displacements are predominant with respect to those in the transverse direction of the bridge, except for the Sylmar record, because the transverse component of this input ground motion is extremely powerful, as it can be seen in **Table 1**. It is also noticed that seismic excitations induce larger deck longitudinal response to S1 than S2. The reason of this is because of the differences in length of the decks. Being observed that collisions occur when S1, which has the larger displacement response, impacts S2 moving both decks in the same direction. This type of impact is relatively benign to the bridge because in case of collisions with decks moving in opposite directions impact forces would expected to be very large[6]. Transverse displacements are observed to be similar for all cases because lateral stoppers are provided for fixed and roller bearings in the transverse component to control the wind-induced displacements of the bridge and consequently, the transversal movement of the superstructures is dominated by the maximum displacement response of the top of P2 which supports both spans.

From the calculated results, it is seen that the effect of restrainers on the highway viaduct seismic response is not significant in reducing the maximum deck displacements. Small observed variations follow the trend that when the peak displacements of one of the spans are slightly decreased, the opossite variation occurs for the other span, increasing a little its maximum displacement response.

5. CONCLUSIONS

The effectiveness of cable restrainers to reduce the seismic structural responses of a two-span simply supported skewed highway viaduct has been investigated through 3-dimensional nonlinear dynamic analysis.

The obtained results indicate that special attention should be paid to the exterior girders in the seismic design of multi-span simply supported skewed bridges. Large reaction forces are attracted by the bearings supporting the exterior girders due to the natural tendency of skewed bridges to coupled translational-rotational displacements. Moreover, it is clearly observed that this differential behaviour could be sensibly magnified with the adoption of cable restrainers, and the concentration of loading to specific bearings is expected to increase the vulnerability to failure of the supports, thus also increasing the possibility of deck unseating in the event of large earthquake ground motions.

It is concluded that restrainers are effective in achieving significant reductions in the maximum separation between adjacent spans. In addition, restrainers are capable of reducing the peak displacements of the roller bearings on the pier under the separation joint between decks. However, on the other hand, the continuity provided to the simply supported bridge by the addition of restrainers may increase the maximum displacements of the roller bearing supports of adjacent piers, and unseating of the deck superstructure could occur at those pier locations.

The skewed bridge configuration results in large bending moments at base of the piers in the transverse direction. The presence of restrainers does not modify significantly the seismic response of the piers, since the link elements act as a transmitters of the seismic loads, and the global damage to the substructure elements is similar in case of restrainers are installed or not. The influence of restrainers on the peak deck displacement response is also small, and it is not expected to be affected by the stiffness of the restrainers.

The above considerations indicate that the seismic behaviour of multi-span simply supported skewed highway viaducts is sensibly complicated. The response of this type of bridges under large earthquakes could be affected by many factors, and it is the purpose to extend this study considering for the next step the effect of skew angle, bearing supports orientation, base isolation and two-sided pounding.

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