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SEISMIC RESPONSE OF GIRDER BRIDGES WITH UNCONVENTIONAL CONFIGURATIONS

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SUMMARY

In this paper, the seismic response of a multi-span continuous deck highway bridge with an unconventional configuration was evaluated. It shows that a strong longitudinal earthquake can lead to out-of-phase vibration of adjacent bridge segments due to differences in dynamic characteristics. This out-of-phase vibration results in a large relative displacement and pounding force between adjacent bridge decks at expansion joints. Pounding amplifies the response of a pier with low height. Furthermore, a measure for reducing out-of-phase vibration and pounding between adjacent bridge decks at an expansion joint was introduced.

INTRODUCTION

The west mountainous areas of China are the high seismic zones. In these areas, many multi-span continuous deck highway bridges have been built crossing mountain valleys. Because of the rugged topography, bridge piers are of unequal height with the highest pier in the middle, and the height of piers from the highest to the shortest varying greatly, resulting in an irregular configuration. A typical configuration for these bridges is shown in Fig.1. The multi-span continuous deck is separated by expansion joints to several bridge segments in the longitudinal direction. The tall piers are located in the middle segment and the short piers are located in sides. For a bridge with such a configuration, the difference in dynamic characteristics between the middle and side segments will result in out-of-phase vibrations under a strong longitudinal earthquake. This out-of-phase vibration can lead to a larger relative displacement and pounding between adjacent girders at expansion joints.

In this paper, out-of-phase vibration effects on structure seismic response, especially on the relative displacement and pounding force at an expansion joint were investigated with an nonlinear seismic response history method.

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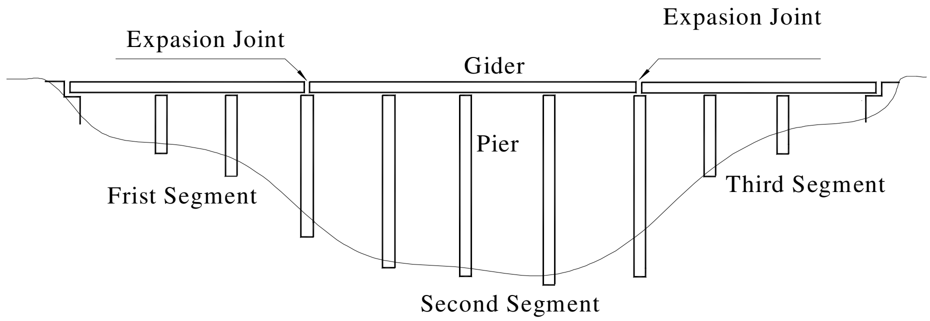


Fig.1. A typical multi-span continuous bridge at west mountainous areas

ANALYTICAL MODELING

A typical reinforced concrete highway bridge investigated in this study has fourteen equal spans. Each span is 30m long and the deck is 14 m wide. The analytical model of this typical highway bridges was shown in Fig.2. The multi-span continuous deck has two expansion joints located at the top of pier3 and pier 10, respectively. There is no longitudinal restrainer to prevent unseating at each expansion joint. The deck is simply rested on elastomeric bearings except pier 6 and pier 7, where the pier to deck connection is monolithic and reinforcement bars from piers are anchored well into the deck. The shear stiffness of elastomeric bearings for each pier is 2.54×10^4kN/m and the height of each pier is shown in Tab.1.

A special computer program DRAIN-3DX [1] was used to perform nonlinear response history analysis of the bridge structure. This program includes several element types that were utilized in this study. An elastic beam-column element was used to model the superstructure, and an inelastic fiber beam-column element was used to model column. Structural damping was model through a combination of stiffness proportional and mass proportional damping. A damping ratio of 5% of critical damping was assumed for the structure. At each expansion joint, a compression-only gap element was used to model impact between adjacent bridge decks (Fig.2b).

The nonlinear force-deformation relationship for a compression-only gap element is given by

$$f = \begin{cases} k(d_0 + x_s) & d_0 + x_s < 0 \\ 0 & ortherwise \end{cases}$$

(1)

where d_0 is the initial gap opening, x_s is the relative displacement between adjacent bridge decks at a expansion joint under an earthquake load, k is the spring constant, which is calculated as an axial stiffness of the superstructure segment [2].

The compression-only gap element damping, *c*, between two masses m_1 and m_2 can be obtained from formula

$$c = 2\xi\sqrt{k\left(\frac{m_1 m_2}{m_1 + m_2}\right)}$$

(2)

where ξ is a damping ratio, its value is correlated with a coefficient of restitution, *e*, which describes the energy dissipation during collision. This relation is given by [3]

$$\xi = \frac{-\ln e}{\sqrt{\pi^2 + (\ln e)^2}} \tag{3}$$

Value of e=1 (ξ =0) describes fully elastic collision, while values of e=0(ξ =0) represents perfectly plastic one. In this study, the value of e=0.65 has been suggested for concrete structures.

Tab.1. Height of piers

Pier number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Height (m)	9.4	21.9	37.9	43.8	46.8	50.9	48.9	39.3	31.8	23.3	17.9	10.8	7.2	6.9

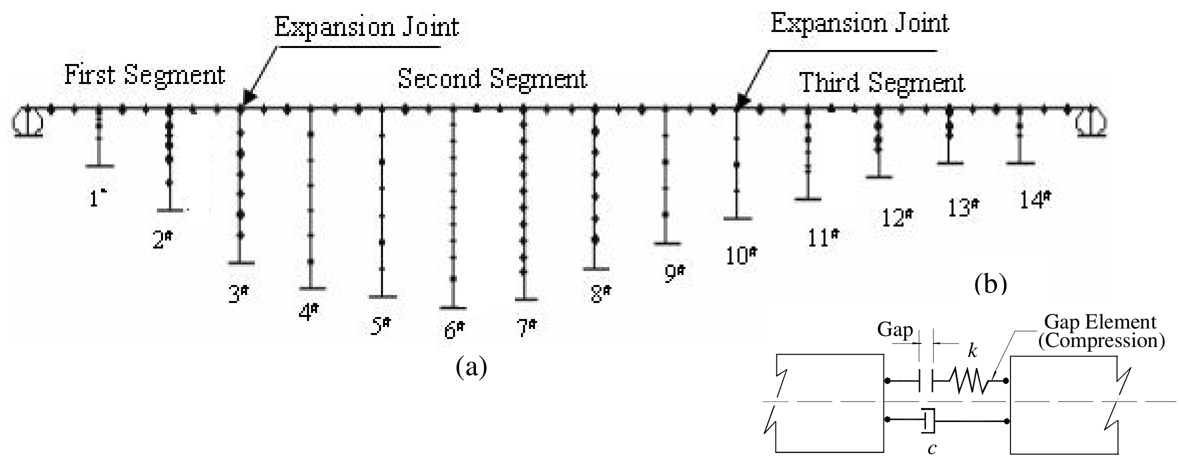
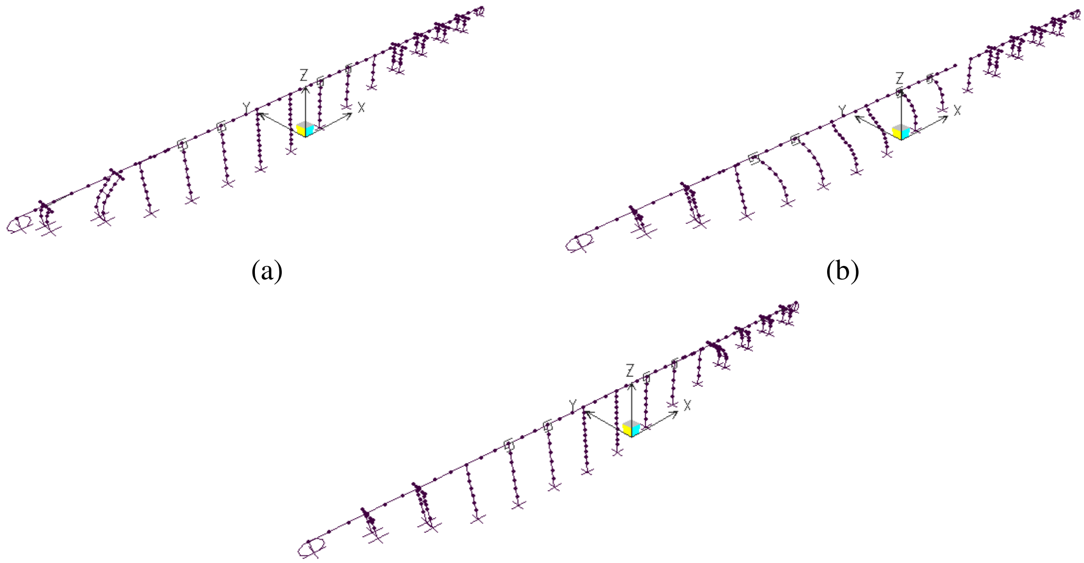


Fig.2. Computer model: (a) Structural model; (b) Expansion joint model

According to above model, the longitudinal foundation periods for three bridge segments are 1.71s (first segment), 2.73s (second segment) and 1.34s (third segment), respectively. Corresponding mode shapes are shown in Fig.3. It is can be seen that the difference of dynamic characteristics in each bridge segment is very large. In this case, out-of-phase vibration of the bridge segments may lead a relative large displacement and impacting force between adjacent bridge decks at expansion joints.

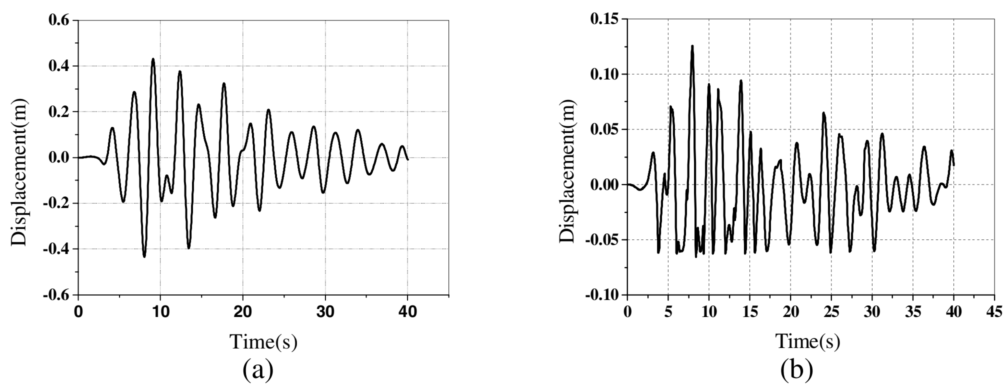
THE POUNDING EFFECTS OF BRIDGE DECKS AT EXPANSION JOINTS

Consider the response of a typical bridge, as shown in Fig.2, subjected to the 1940 EI Centro longitudinal earthquake input, scaled to 0.4g. The initial gap at each expansion joint is 0.06m. The time history of the relative displacement between adjacent decks at left and right expansion joints without and with pounding is shown in Fig.4 and Fig.5, respectively. The responses of the bridge show a large relative displacement between adjacent decks at expansion joints because of out-of-phase vibration. The maximum relative displacements at left and right expansion joints are about 44.2cm and 41.0cm without pounding, respectively. These values are larger than initial gap. So the impact occurs. When pounding are considered, the maximum relative displacements are largely reduced, but a large impact force is induced to bridge decks at expansion joints (Fig.6). Tab.2 shows the peak displacements at top of each pier with pounding and without pounding. The comparison shows that pounding significantly increases maximum displacements of stiff piers. The maximum displacement of pier 2 is increased from 0.134m for the no pounding case to 0.226m for pounding case. Conversely, for flexible piers (piers 6 and 7), pounding reduces maximum displacements.



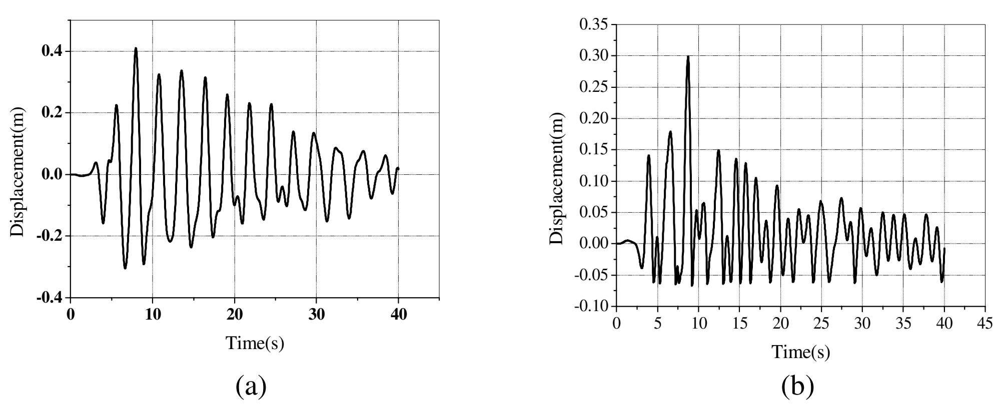
(a) (b) (c)

Fig.3. Longitudinal foundation mode shapes for each segment: (a) mode shape for first segment (1.71s); (b) mode shape for second segment (2.73s); (c) mode shape for third segment (1.34s)



(a) (b)

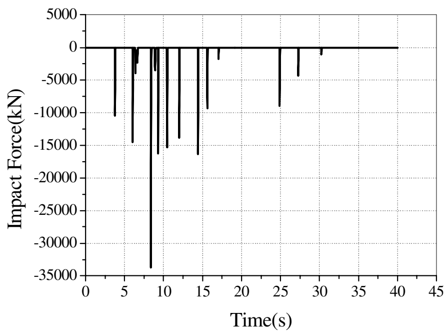
Fig.4. The time history of relative displacements between adjacent decks at left expansion joint: (a) Without pounding effects; (b) With pounding effects



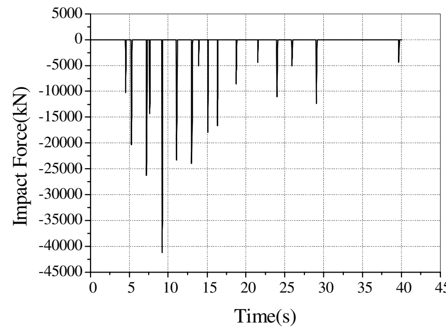
(a) (b)

Fig.5: The time history of relative displacements between adjacent decks at right expansion joint:

(a)Without pounding effects; (b) With pounding effects



(a)



(b)

Fig.6. The time history of impact forces at expansion joints: (a) left joint; (b) right joint

Tab.2. Peak Displacement at the top of each pier

Pier number	1	2	3	4	5	6	7
Displacement(Without pounding) (m) (1)	0.032	0.134	0.180	0.298	0.297	0.322	0.321
Displacement (With pounding) (m) (2)	0.043	0.226	0.180	0.268	0.267	0.271	0.273
(2)/(1)	1.340	1.680	1.000	0.900	0.890	0.840	0.850

Tab.2. Peak Displacement at the top of each pier (Continue)

Pier number	8	9	10	11	12	13	14
Displacement(Without pounding) (m) (1)	0.280	0.276	0.111	0.09	0.045	0.015	0.015
Displacement (With pounding) (m) (2)	0.257	0.256	0.111	0.155	0.068	0.024	0.023
(2)/(1)	0.920	0.930	1.000	1.720	1.510	1.60	1.510

The analytical results show that the pounding have the significant effect on the bridge seismic response. However, there are many parameters, such as ground motion characteristics, bridge segment period ratio and initial gap, have on the response of bridge when pounding effects are included.

PARAMETER STUDIES

To mitigate pounding effects in multi-span continuous deck highway bridges, it is important to determine the factors affecting the pounding response. Although there are many parameters that affect the response of bridge when pounding effects are included, in this study, the principal parameters that are evaluated are the period ratio of adjacent bridge segments and initial gap at expansion joints. The different period ratio of adjacent bridge segments is obtained by varying the shear stiffness of elastomeric bearings on each pier in side bridge segments. Tab.3 shows that the longitudinal foundation period of each segment varies with the shear stiffness of elastomeric bearings. In the response analysis, the 1940 EI Centro and the Norbridge earthquake, scaled to 0.4g were considered as ground motion input.

Pounding Effects on Displacements of Piers

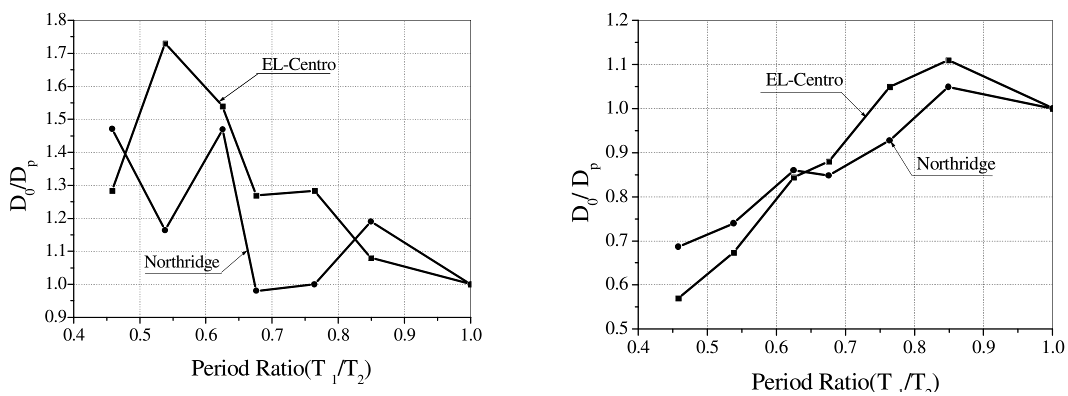
The effect of pounding is expressed in term of the displacement amplification ratio, which is the ratio of the maximum pounding displacement to the maximum displacement if pounding doses not occur. Fig.7 shows a plot of the displacement amplification ratio as a function of period ratio of adjacent bridge segments when the initial gap is 0.06m. Pounding increases the displacement of low piers (pier 2) and reduces the displacement of tall piers. The maximum increase in response of the low pier is about 75%. The period ratio has a significant effect on displacement response of the pier. When period ratio varies from 0.55~1.0, the pounding response reduces as the period ratio increases on the whole.

Tab.4 shows the displacement amplification ratio at the top of pier 2 for initial gap d=0.03m, d=0.06 and d=0.12m. In this case, the period ratio is 0.67. It can be seen from Tab.4 that the initial gap has some effects on the displacement response of the pier, but it is not significant.

Tab. 3. Foundation period of each bridge segment varying with the shear stiffness of bearings

Case	1	2	3	4	5	6
Shear stiffness of bearings for each pier in first segment (kN/m)×10^4	7.00	4.00	2.00	1.40	1.05	0.70
Shear stiffness of bearings for each pier in third segment (kN/m)×10^4	3.50	2.00	1.15	0.85	0.65	0.45
Foundation period for first segment T_1(s)	1.253	1. 472	1.848	2.09	2.321	2.700
Foundation period for third segment T_3 (s)	1.199	1.465	1.819	2.06	2.310	2.720
T_1/T_2	0.46	0.538	0.676	0.764	0.849	0.988
T_3/T_2	0.44	0.536	0.665	0.75	0.845	0.995

Note：T_2 is the foundation period of the second segment



(a) (b)

Fig.7 Maximum displacement response of pier：(a) pier 2；(b) pier 6；

Tab.4 Displacement amplification ratio at the top of pier 2 for initial gap

Period ratio	EL-Centro			Norbridge		
	d_0=0.03m	d_0=0.06m	d_0=0.12m	d_0=0.03m	d_0=0.06m	d_0=0.12m
0.460	1.24	1.28	1.22	1.62	1.47	1.35
0.538	1.75	1.73	1.54	1.28	1.17	1.11
0.676	1.33	1.27	1.34	0.99	0.98	1.16
0.764	1.27	1.08	1.28	1.08	1.19	1.04
0.849	1.11	1.08	0.91	1.2	1.19	1.18

Pounding Force at Expansion Joints

Fig.8 shows a plot of the maximum pounding force at each expansion joints as a function of period ratio of adjacent bridge segments when the initial gap is 0.06m. The results indicate that the maximum pounding force reduces significantly as period ratio increases on the whole. The maximum pounding force at expansion joints with different values of the gap is shown in Fig.9 It is can be seen that the small gap size increase the pounding force.

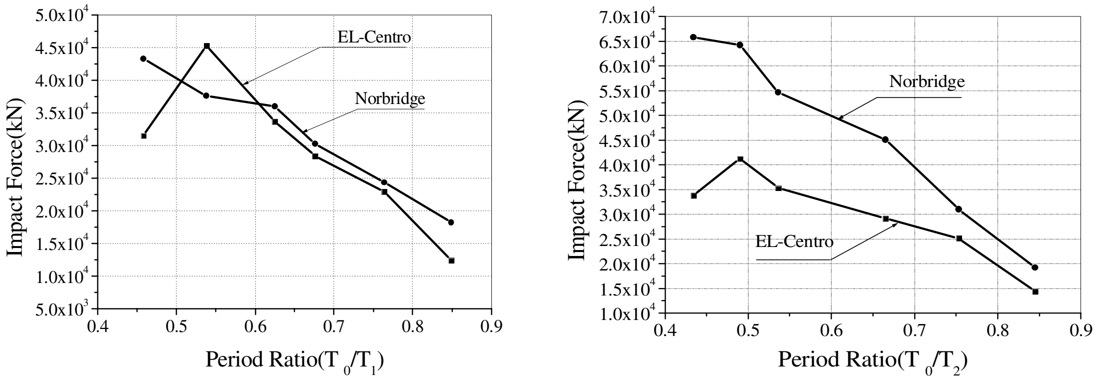


Fig.8 Pounding force with different bridge segment period ratio:
(a) Left expansion joint; (b)Right expansion joint

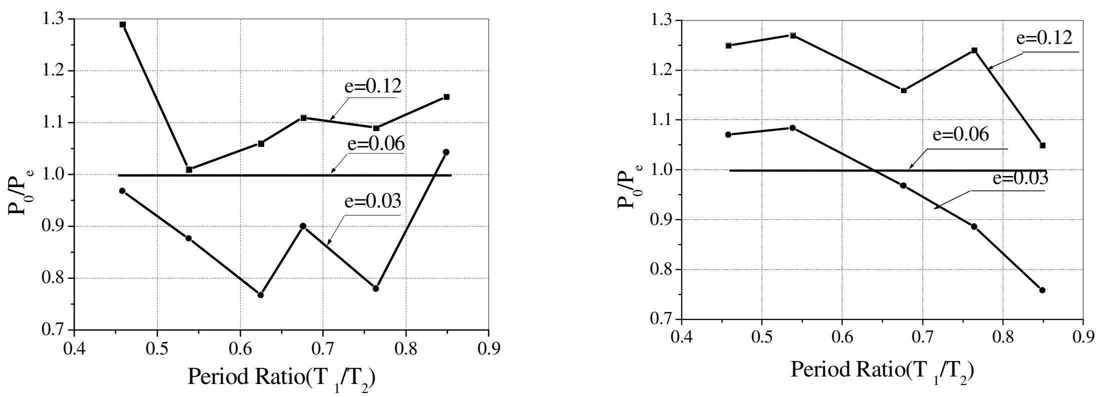


Fig.9 The maximum pounding forces with different values of the gap:
(a)EL-Centro; (b)Norbridge

REDUCTION OF POUNDING EFFECTS

The above analytical results show that out-of-phase vibration can result in pounding and large relative displacement at the expansion joint. This pounding may result in structural local damage at expansion joints and amplify the response of pier with low height. In order to reduce the negative effects of pounding, a connection device as shown in Fig.10 is adopted at each expansion joint. The device consists of rubber pad, elastic spring and link bar.

If the connection device was adopted, the computer model of an expansion joint includes a compression-only gap element and a tension-only hook element as shown in Fig.11. The nonlinear force-deformation relationship for a tension-only gap element is given by:

$$f = \begin{cases} k_h(x_s - d_0) & x_s - d_0 < 0 \\ 0 & \end{cases} \tag{4}$$

where d_0 is the initial gap opening, x_s is the relative displacement of adjacent girders at expansion joints under earthquake loads, k_h is the spring constant, which is calculated as an axial stiffness of of elastic spring.

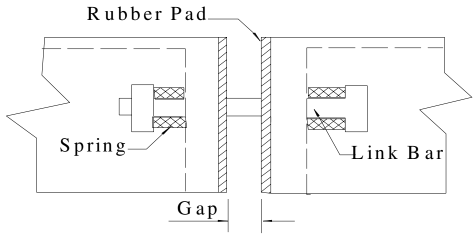


Fig.10. Connection device

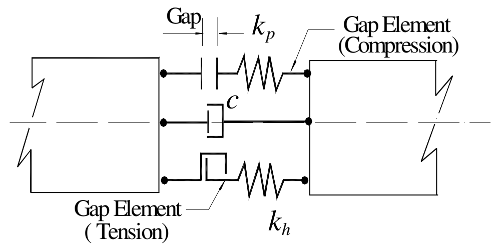


Fig .11. Computer model for expansion joint

For the computer model that shown in Fig.2, subjected longitudinal EL-Centro and Norbridge earthquakes, the comparison of the displacement with and without connection device for the piers 2, 6 and 11 is shown in Tab.5. The impact forces and relative displacements of adjacent bridge decks at expansion joints are shown in Tab.6. The results show that although the connection device has a small effects on the displacement of piers, it reduces impact forces and relative displacements of adjacent bridge decks at expansion joints significantly.

Tab.5. Effects of connection device on displacement of piers

Case	EL-Centro			Norbridge		
Pier number	2	6	11	2	6	11
With device	0.181m	0.246m	0.166m	0.258m	0.323m	0.20m
Without device	0.226m	0.271m	0.155m	0.239m	0.345m	0.21m

Tab.6. Effects of device on impact forces and relative displacements of adjacent bridge decks

Case		EL-Centro		Norbridge	
		Left joint	Right joint	Left joint	Right joint
Relative Disp(m)	With device	0.0758	0.0874	0.0723	0.0939
	Without device	0.1260	0.299	0.241	0.423
Impact Force(kN)	With device	14620	24540	11770	26880
	Without device	33700	41230	35990	64200

CONCLUSIONS

This paper has investigated out-of-phase vibration of bridge segments in a bridge with a conventional configuration subjected longitudinal earthquakes. The effects of pounding of adjacent decks at expansion joints are emphasized. The primary factors affecting the pounding response are identified as the period ratio of adjacent bridge segments and initial gap of expansion joints. Strong longitudinal earthquake can led to larger relative displacements and impact forces between adjacent bridge decks at expansion joints due to the differences of dynamic characteristics. Pounding amplifies the response of pier with low height and reduces the displacement of tall piers. Furthermore, the connection device can reduce the relative displacement and pounding force at expansion joint significantly.

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