VERTICAL COMPONENT EFFECT OF EARTHQUAKE IN SEISMIC PERFORMANCE OF REINFORCED CONCRETE BRIDGE PIERS

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ABSTRACT :

Reinforced Concrete (R.C.) bridges with single piers have been used extensively in Iranian highways similar to the other countries. Sever damage of this kind of piers during past earthquakes in Japan, USA, New Zealand and other countries indicates inadequacy of seismic design and construction requirements. After 1995 Kobe earthquake in Japan and extensive damage of Hanshin highway bridge piers, the vertical component effect of earthquake ground motions is considered as an important parameter for vulnerability of R.C. bridge piers. In this paper, these effects have been studied in a bridge with single piers using nonlinear dynamic analyses. Horizontal and vertical component of the 1978 Tabas earthquake in Iran have been used as input ground motion. Analytical results indicate more than 30 percent increases in axial forces. Changing the ductile bending cracking pattern to brittle shear cracking pattern due to the vertical component effect of earthquake ground motion is another important observation.

KEYWORDS: Reinforced concrete bridges, vulnerability, bridge piers, Vertical component effect, earthquake

1. INTRODUCTION

Extensive damage of highway bridges in recent decades and during the recent earthquakes such as loam Prieta (1989), North rich (1994) and Hyogoken-Nanbu or Kobe(1995), lead to new revisions in bridge design codes in many countries such as Japan and USA. In recent revisions of bridge design codes, Performance based seismic engineering is included as a modern approach to earthquake resistant design. Rather than being based on prescriptive mostly empirical code formulations, performance based design is an attempt to predict buildings with predictable seismic performance. In addition, vertical component effect of earthquake ground motions is another considerable parameter in seismic vulnerability and strengthening of bridge structures. The main objective of new revisions in code requirements is increasing of ductility demands and restriction of brittle failures due to strong earthquakes [1, 2, 3, and 4].

Extensive damage study of bridge piers during the Hyogoken-Nanbu earthquake (1995) by different researchers shows that the damages observed in Hansen highway bridge piers is as bending-shear failure mode in middle of piers. The main reason of this kind of damage is nonlinear behavior and plastic hinge formation in piers. This behavior was not considered in linear analyses during design stages. In addition, effective length of reinforcing bars was not enough due to diagonal shear cracking of R.C. bridge piers and reversed stresses introduced by earthquake motions.

Vertical component effect of earthquake ground motion is another important parameter in seismic vulnerability and damageability of bridges which was not considered in old revisions of design codes. Due to vertical component of earthquake ground motions, the axial tension forces can cause a diagonal shear failure in piers. In the case of axial compression forces, the total load bearing capacity is increases, but the ductility capacity of piers is reduces due to concrete crushing in locations of diagonal cracking. Experimental investigations show that the impact effects of vertical component of ground motions generate helical cracking in R.C. bridge piers [1].

Many instances of Hyogoken-Nanbu earthquake (1995) in adjacent of Hansen highway explained an evidence of vertical motions of deck and bridge piers of this highway. Extensive damages of this important highway bridge piers, lead to important modifications in design code requirements of bridges. Displacement based design instead of ancient force based design was one of these modifications. Also, consideration of the vertical component effects of earthquake ground motion was another requirement in new seismic design code of bridges. In this paper, the effects of vertical component of earthquake ground motion have been studied using nonlinear dynamic analyses. For this purpose, finite element analyses of an existing R.C. bridge pier before and after retrofitting have been made. Horizontal and vertical component of the earthquake ground motion is considered simultaneously as input motions of the models.

2. ANALYTICAL MODELS

Studied bridge in this paper was constructed from several R.C. single piers and R.C. deck. Connection of pier to foundation and deck is considered as fixed connection. Dead and live loads of deck are considered as equivalent continues load applied on transverse girders on top of piers. Only one pier and equivalent loads is considered in analytical model.

Tow different pier models named model A, and B investigated in this study. Model A indicate the original and non retrofitted pier as constructed in 1964 and damaged during Hyogoken-Nanbu earthquake. Model B is retrofitted pier after earthquake in 1996 to resist future strong earthquakes. General view of finite element model of pier and deck girder is shown in Figure 1. Cross section properties of Pier in model A and B are illustrated in Figure 2. Summary of these properties are shown in Table 1.

Table 1 Section properties of Pier in model A and B

model	Dim. (m)	Steel Bars Diameter (mm)	Long. Bar Ratio (%)	Shear Bar Ratio (%)	Pier Height (m)	Deck Load (MN)
A	2.4×1.9	88 D29	1.24	0.80	12.5	4.90
B	2.9×2.2	116 D38	2.08	1.08	12.5	4.90

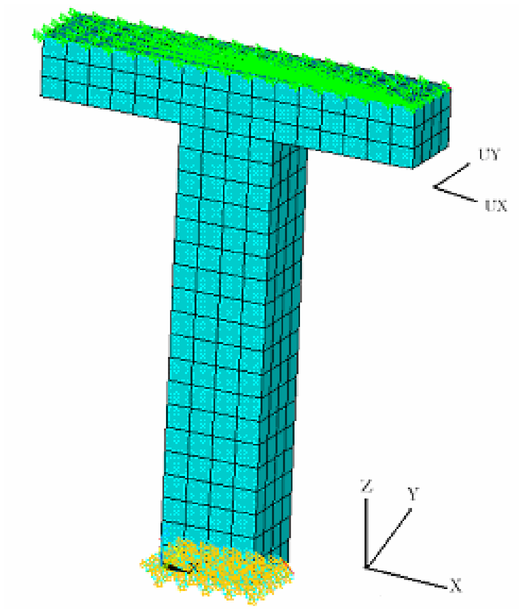
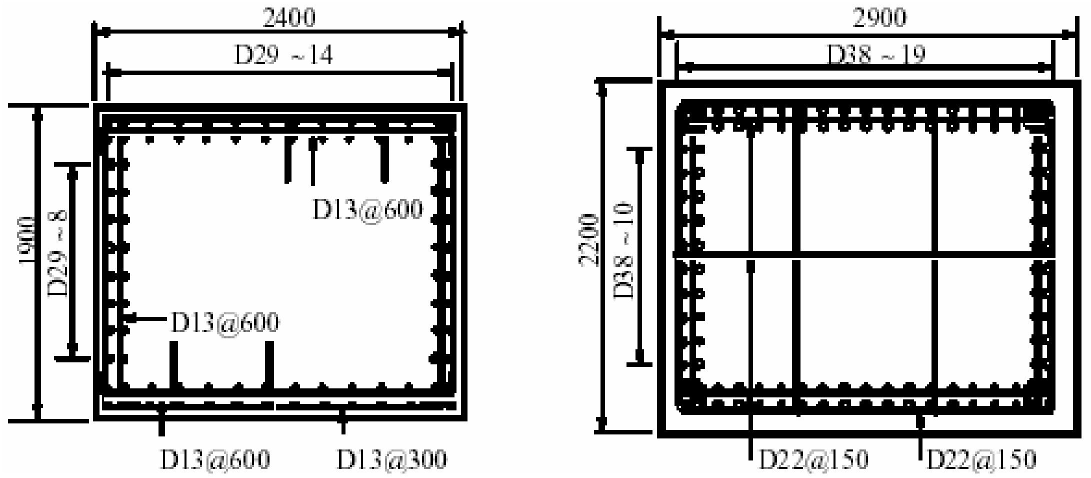


Figure 1 General view of analytical models A and B

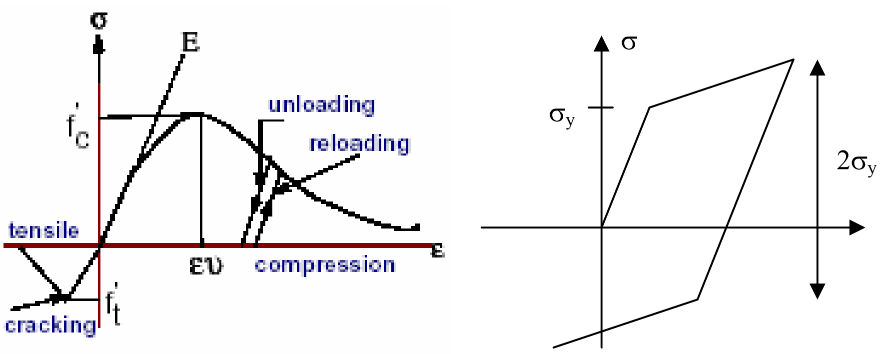


Model A Model B

Figure 2 Cross section properties of pier in models A and B

Finite element model is used for modeling of R.C. piers and deck girder in order nonlinear dynamic analyses. Solid element is used for modeling of concrete and reinforcement bars and mass element is used for definition of deck masses in different directions. Nonlinear models for concrete and steel reinforcement are considered as shown in Figure 3. Some important characteristics of material nonlinearity are as follows [5]:

- Steel bars can bear axial forces in tension or compression
- Stress-strain relationship of concrete is multidirectional
- Complete bonding between concrete and steel bars is considered
- Symmetric bilinear model is considered for steel reinforcement



a) Concrete b) Steel reinforcement

Figure 3 Nonlinear models for a) Concrete and b) Steel reinforcement

3. ANALYSES RESULTS

Dead and live loads are applied as static loads. The result of static analyses is considered as initial condition for dynamic analyses. Both models (A and B) is subjected to base acceleration of 3 component accelerometers recorded from 1978 Tabas earthquake in Iran with magnitude of 7.7 in order to nonlinear dynamic analyses. Horizontal and vertical component of this record is shown in Figure 4. Horizontal component of this record with Peak Ground Acceleration (HPGA) with 0.1g, 0.3g, and 0.5g is applied to the analytical models (g is gravity acceleration). Vertical Peak Ground Acceleration (VPGA) equal to 50% of horizontal component is used in dynamic analyses.

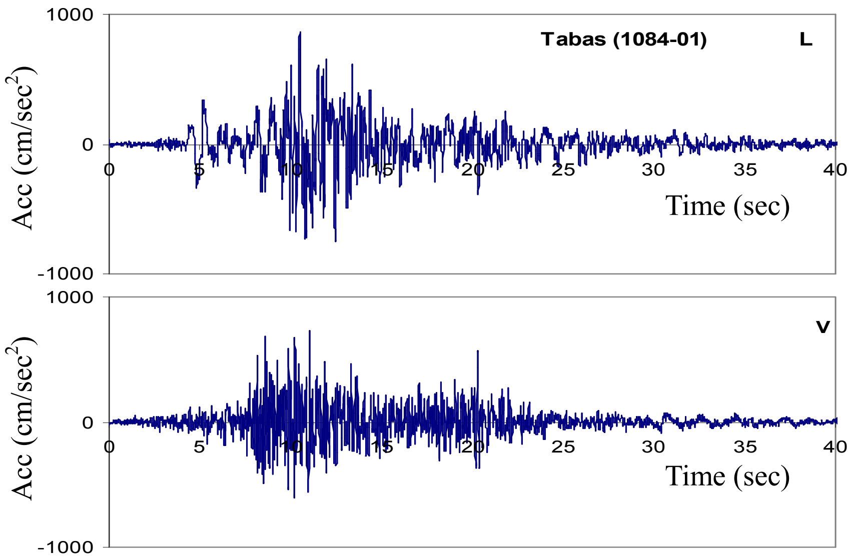


Figure 4 Horizontal (L) and vertical (V) component of Tabas record

The results of axial force-bending moment interaction diagram (P-M) for model A and B is shown in Figure 5 and Figure 6. As shown in these figures, the P-M interaction point in model A (original model) is very close to the interaction surface. However, there is more safety factor in the case of model B (retrofitted model). Interaction points are obtained from 0.5g peak ground acceleration record.

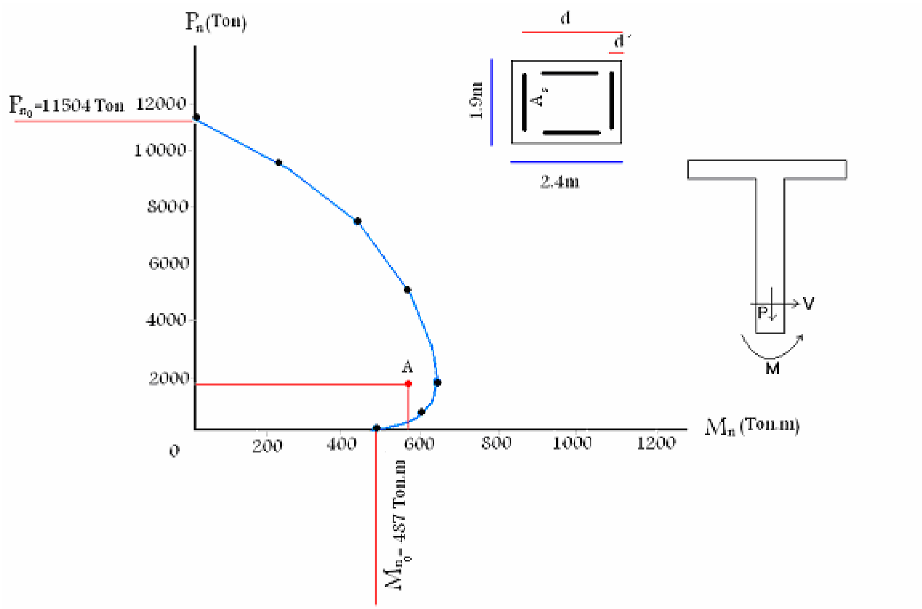


Figure 5 P-M diagram of pier in model A

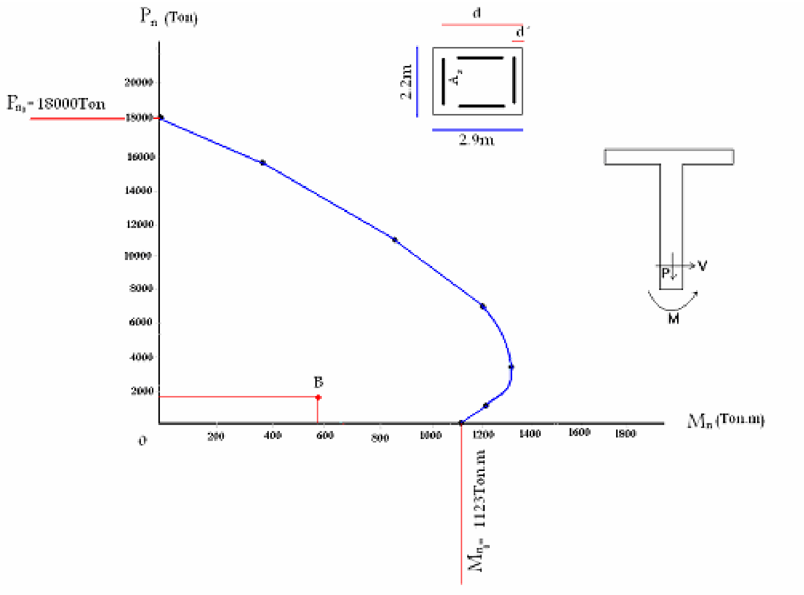


Figure 6 P-M interaction diagram of pier in model B

The results of deck lateral displacement time history due to o.3g peak ground acceleration record in model A in the case of only horizontal (H) and horizontal plus vertical (H+V) component effects are shown in Figure 7 and Figure 8 respectively. As shown in these figures, maximum lateral displacement of deck is increased about 3% due to vertical component of earthquake. Some residual displacements are shown in results due to nonlinear behavior of materials in strong ground motion region. Similar results are obtained for model B.

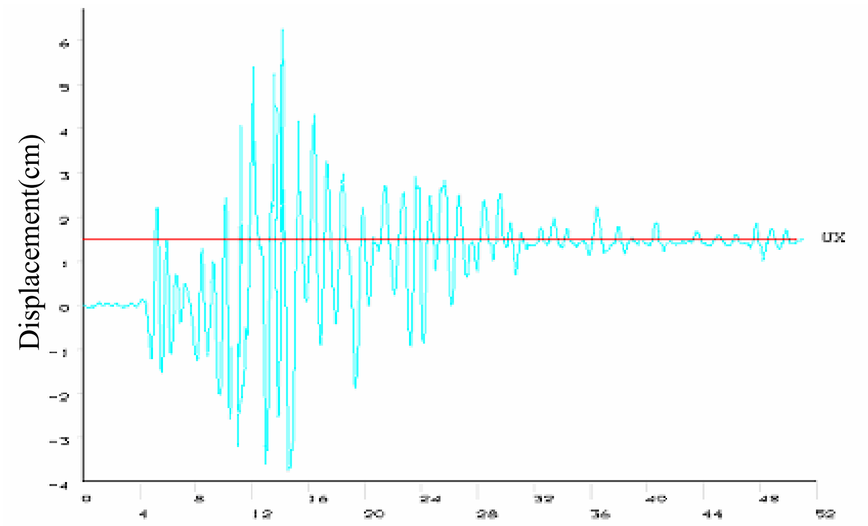


Figure 7 Deck lateral displacement time history of model A subjected to H component of Tabas record with PGA=0.3g.

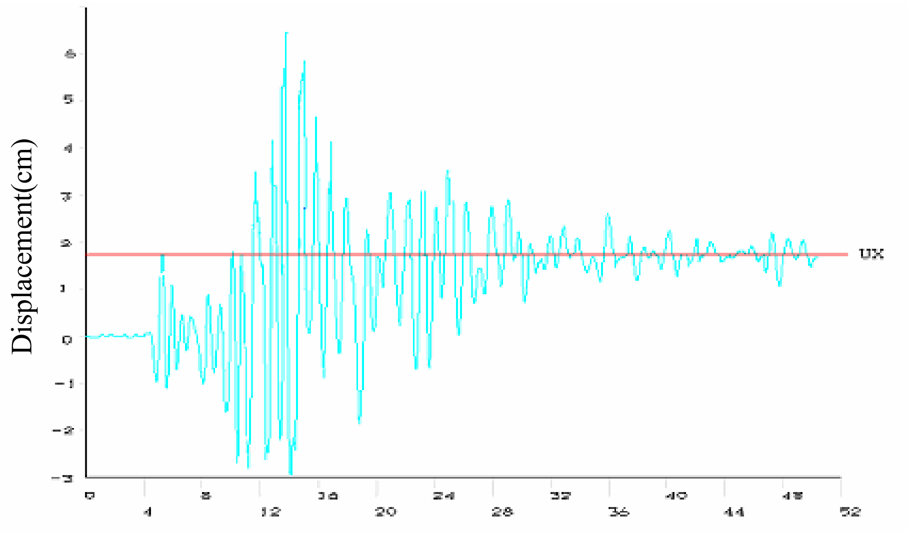
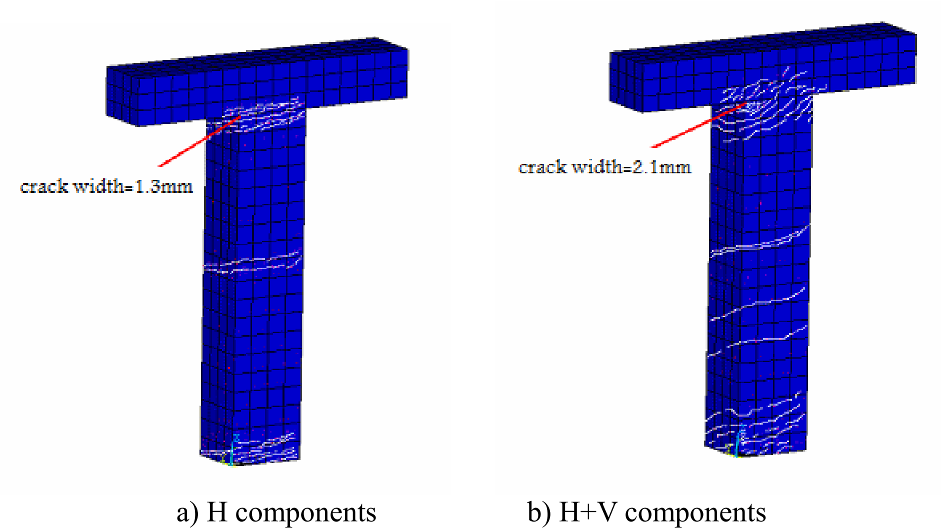


Figure 8 Deck lateral displacement time history of model A subjected to H+V component of Tabas record with PGA=0.3g.

Crack pattern of model A due to o.5g peak ground acceleration record is shown in Figure 9. As shown in this figure, the crack width is increased about 60% due to vertical component of earthquake. In addition, crack pattern is oriented from bending cracking to diagonal shear cracking due to vertical component effects of ground motion.



a) H components b) H+V components

Figure 9 Crack pattern of model A subjected to a) H components and b) H+V components of Tabas record with PGA=0.5g.

A summary maximum response of forces and displacements obtained from nonlinear dynamic analyses of model A and B subjected to horizontal and vertical component records of Tabas earthquake ground motion are shown in Table 2. In this Table, P, M, and V are base axial force, bending moment, and shear forces respectively. In addition D indicates deck lateral displacement.

Table 2 Maximum responses of model A and B subjected to Tabas record

Model	HPGA	0.1g		Difference (%)	0.3g		Difference (%)	0.5g		Difference (%)
	Earthquake Component	H	H+V		H	H+V		H	H+V	
A	P (ton)	530	680	28%	980	1270	29%	1305	1686	29%
	M (ton.m)	120	128	6.6%	296	317	7%	512	568	10.9%
	V (ton)	68	76	11.7%	126	143	13.4%	165	189	14.5%
	D (cm)	3.97	4.1	3.2%	6.45	6.64	2.9%	8.72	8.98	2.9%
B	P (ton)	540	702	30%	1053	1366	29.7%	1381	1788	29.4%
	M (ton.m)	133	141	6%	335	360	7.4%	535	588	9.9%
	V (ton)	70.5	78	10.6%	129	145	12.4%	173	197	13.8%
	D (cm)	2.83	2.92	3.1%	5.93	6.11	3%	8.31	8.56	3%

4. CONCLUSIONS

Refined nonlinear dynamic analyses have been made on an existing R.C. bridge pier before and after retrofitting using horizontal and vertical components of 1978 Tabas earthquake. Based on these analyses, the maximum axial force of pier is increased about 30% due to vertical component effect of earthquake. These increasing effects for maximum bending moment and maximum shear force of pier are 10% and 15% respectively. In addition, the crack width is increased about 60% due to vertical component of earthquake with changing of crack pattern from bending to diagonal shear cracking. However, the result of this analytical research shows that the vertical component of earthquake is an important parameter and should be considered in design of bridge structures.

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