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DUCTILITY DEMANDS OF ISOLATED REINFORCED CONCRETE BRIDGE PIERS PLACED IN MEXICO CITY

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ABSTRACT

The investigation reported in this paper is an attempt to assess the relevance of the rotational inertia of the transversal girder effects on the dynamic behavior of bridge piers responding in the inelastic range, in order to study the ductility demands of the reinforced concrete bridge piers.

The article presents numerical results of the seismic response of the bridges placed in different zones of Mexico City, in order to enhance the understanding of the inelastic behavior. Ground motions recorded in soft and rock sites, during the earthquake occurred in 1985 in the Pacific coast were used for the ductility studies through the inelastic behavior. The inelastic energy dissipated within the structure and the maximum lateral displacement attained at the free-end of system, are the bases for comparison and analyses of the response of the bridges. The step-by-step inelastic dynamic analyses were carried out, using the DRAIN-2DX program.

KEYWORDS

Bridges; bridge piers; ductility demands; dynamic behavior; reinforced concrete; seismic behavior.

INTRODUCTION

Procedures for seismic design specified in building codes have been developed and based upon studies made for regular structures, principally buildings placed in urban zones. Then, the extrapolation of these recommendations to structures other than buildings is not completely justified unless detailed studies are made. This is the case for special structures such as highway bridges.

Despite intensive researches the seismic behavior of bridge structures (free-end of system carrying a mass at the top), the basic approaches to seismic design remain much the same, in the buildings codes. Response modification factors to account for ductility have been obtained from the study of SDOF systems and regular structures. However, there are not some broads specific in codes about response modification factors, to account for ductility demands for isolated bridge piers. Design recommendation may be underestimate strength and deformation demands, particularly for short-period bridge and for bridges on soft soils.

Besides, this research attempts to study the inelastic seismic response of bridge piers, with the purpose to estimate the ductility demands of these structures placed in rock and soft soil of Mexico City. Special emphasis is placed on the rotational inertia effect of the deck bridges in the global seismic behavior.

DYNAMIC BEHAVIOR

Really, the isolated bridge piers present at the top a great and long deck (mass). Seismic behavior of this type of structure should be studied, taking into a count in the total motion, the rotational inertia effect produced by the rocking of the superstructure. This dynamic behavior generated by the deck, modified and increased the dynamic parameters such as the frequency and the periods of the structures. The aim of this research is to show the rotational inertia influence on the total motion although of the numerical analysis in the elastic and inelastic range using the strong-motion records of Mexico City and Guerrero coast.

Elasto-dynamic model and equations of motion (Rigid foundation)

Dynamic model is a typical elastic oscillator with a rigid foundation. The pier is modeled as two DOFs oscillator characterized by a mass distributed a long of the superstructure, a lateral restoring force and another rotational restoring force. The deck is assumed as rigid diaphragm. The mass **m** equals the weight of the supported deck plus a fraction of the weight of the column. The column is assumed to respond elastically all thorough its height, and the rotational inertia **J** of the girder of the neck are taking into a count. The moving of the structure is studied through of the two perpendicular directions to themselves. The problem is discretized in two DOFs coupled at the top of the end.

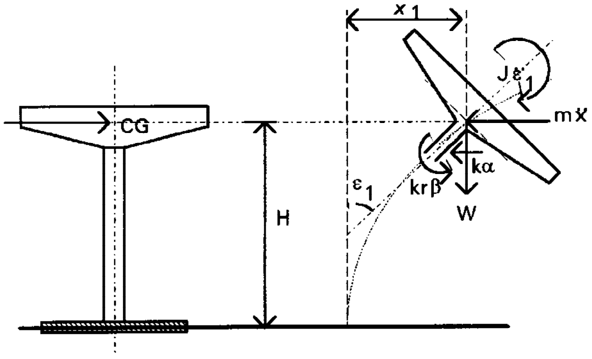


Fig. 1.

The equations of motion of the two DOFs system are:

$$m\ddot{x}_1 + k\alpha = 0 \qquad (1)$$
$$J\ddot{\varepsilon}_1 + k_r\beta = 0$$

the solution of this system gives the frequency equation (Rascón, 1965):

$$\omega_{1,2}^2 = 2\left(p^2 + \Omega^2 \pm \sqrt{(p^2+\Omega^2)^2 - p^2\Omega^2}\right) \qquad (2)$$

$$T_1 = \frac{2\pi}{\omega_1} \qquad (3)$$

were:

$p^2 = k / m =$ square of the circular frequency of translation

$\Omega^2 = k_r / J$ = square of the circular frequency of rotation
k = unitary stiffness of translation spring at the top of the pier
k_r = unitary stiffness of rotation spring at the top of the pier
T_1= fundamental period

Non-linear analysis

In order to know the response and non-linear behavior of the concrete bridge pier, the step-by-step inelastic dynamic analysis were carried out using the DRAIN-2DX program (Prakash *et al.*, 1992).

The structures are modeled in 2D (see figure 2), the pier stem and the tapered girders are discretized in sections with the objective to study its behavior and state of stress, considering a rigid foundation, taking into account the shear deformation, as well as the variation of the stiffness of the tapered girders and the rotational inertia of them.

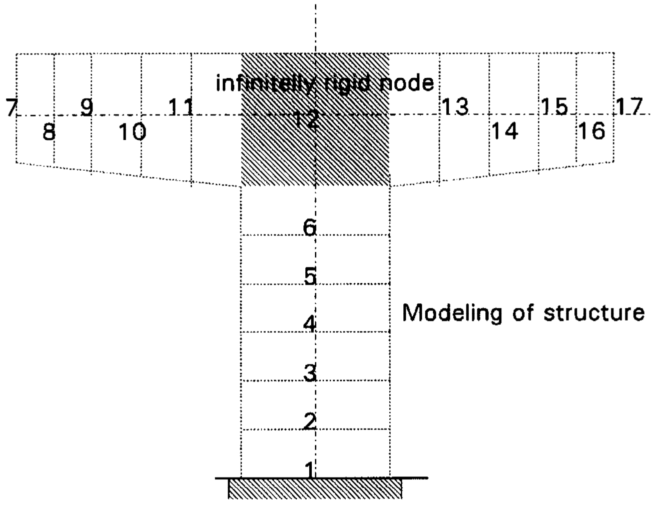
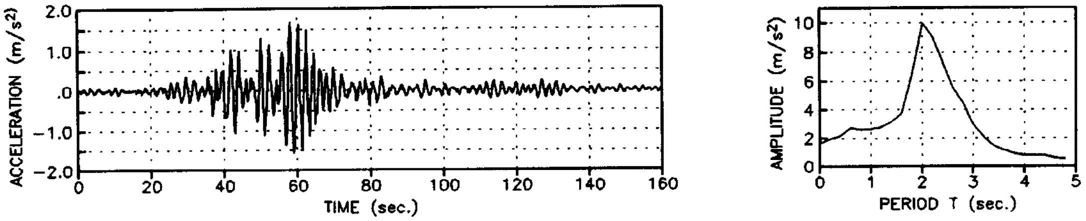


Fig. 2. Modeling of structure

A bilinear strain hardening model is adopted in all numerical analysis, strain hardening ratio is chosen as 0.10 of Young's Modulus. Interaction surface (force-moment) of the column was calculated in function of the longitudinal steel ratio (axial reinforcement).

Strong-motion Records

Ground motion records in soft and rock sites during the earthquake of 19 September 1985, occurred in Mexican Pacific coasts are chosen and used for the ductility studies through the inelastic behavior (see figure 3). The structures are analyzed with these accelerogram records, obtaining different responses in function of the dynamic parameters.



(a)

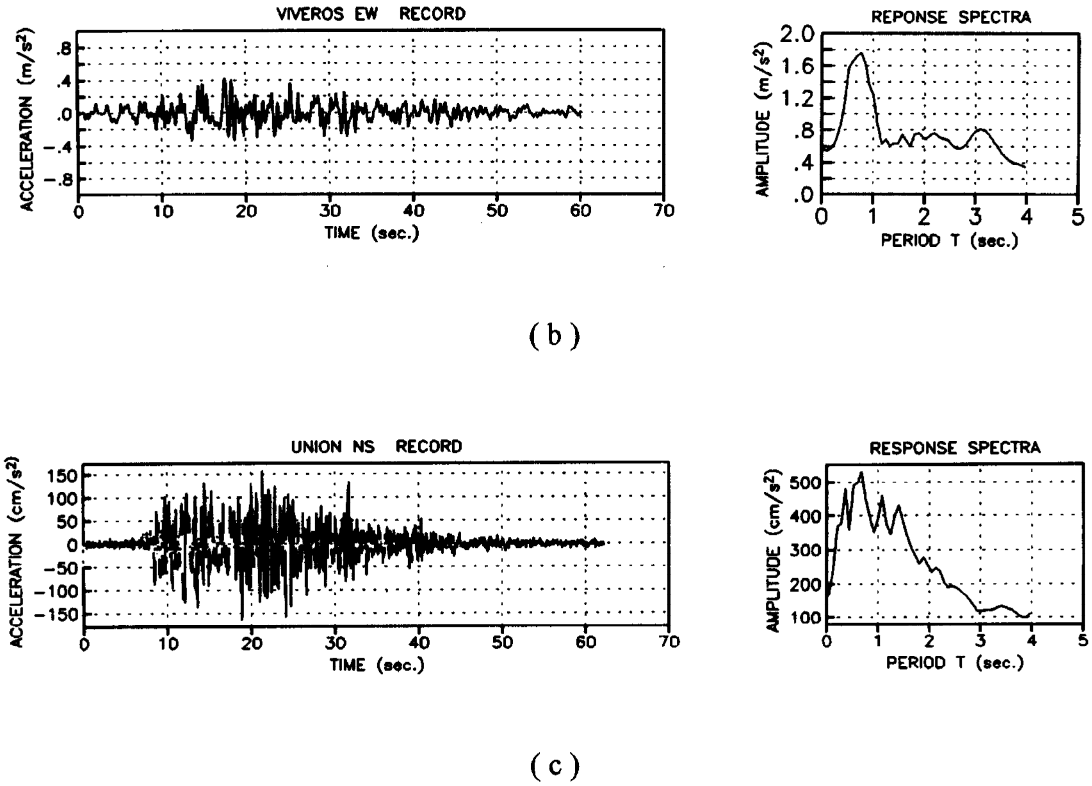


Fig. 3. Strong motion records and linear elastic spectra with 5% damped.

Table 1. Strong-motion records

Record	Site	Date	Station	Direction
1	Mexico City	19/09/85	SCT	E-W
2	Mexico City	19/09/85	Viveros	E-W
3	Guerrero coast	19/09/85	Union	N-S

STRUCTURES STUDIED

As mentioned in the introduction, the main purpose of this work is to asses the influence of the rotational inertia, on the seismic behavior of isolated reinforced concrete bridge piers responding in the inelastic range, in order to estimate the ductility demands.

The rotational inertia effect of the deck is analyzed in two structures with different geometrical characteristics. The structures studied are illustrated in figure 4.

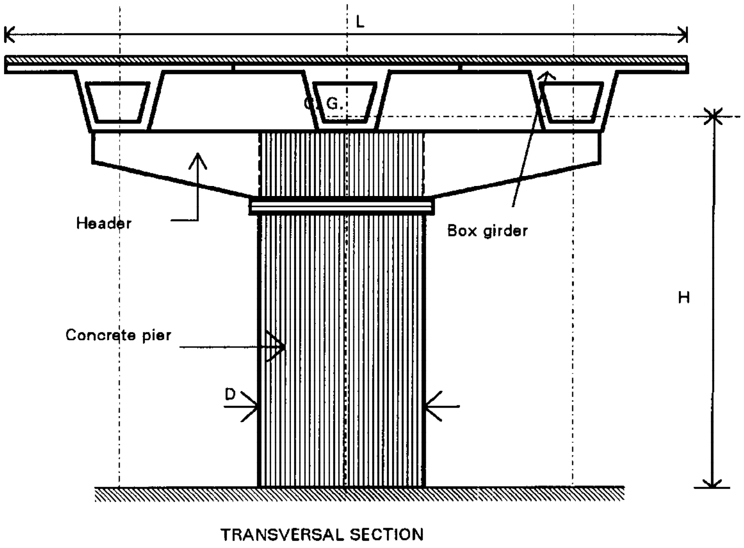


Fig. 4. Typical section

Table 2. Characteristics of the structures

Structure	L (m)	H (m)	Weight (MN)	Pier section	D (m)
A	12	7.30	**4.6** (470 Ton)	circular oblong	1.75
B	20	12.30	**11** (1100 Ton)	circular	3.10

Table 3. Details of the reinforced piers.

Structure	Materials strength			Longitudinal steel ratio	Transversal steel ratio
	f'_c (Mpa)	f_y (Mpa)	f_{yh} (Mpa)	$\rho_l x10^{-3}$	$\rho_s x10^{-3}$
A	29.44	412	412	4.0	3.48
B	35	350	350	2.28 - 1.52	1.38

NUMERICAL RESULTS

Equivalent lateral force procedure

Seismic shear Vs, overturning moment M_b and head rocking moment M_c at the top of the column were calculated, by the equivalent lateral force procedure, considering the seismic coefficients recommended by the RDF Mexican Building code (RDF, 1990).

Table 4. Seismic coefficients

Zone	c	Site
I	0.16	Rock
II	0.32	Transition
III	0.40	Soft

The influence of the head rocking moment M_c at the top of the column, toward overturning moment M_b (M_c / M_b) is about 29% from 33% of the structures A and B respectively, for all zones.

Modal dynamic elastic analysis

Fundamental periods are obtained to apply the modal elastic analysis of a two DOFs oscillator with rigid foundation and taking into account the rotational inertia at the top of the pier.

Table 5. Fundamental period

Structure	Fundamental period			M_c / M_b		
	T_C	SDOF system T_S	T_c / T_s	Zone I	Zone II	Zone III
A	0.263	0.203	1.29	0.2516	0.2508	0.2575
B	0.6145	0.50	1.23	0.3031	0.2935	0.2846

In table 5, the fundamental period ratios T_C / T_S are shown, observing an increase about 29% and 23% of the structures A and B respectively, in relation to a SDOF system T_S. This increase is due to the rotational inertia effect on the all seismic behavior. The ratio of the head rocking moment M_C at the top of the pier with respect to overturning moment M_b is about from 25 to 30% in all cases.

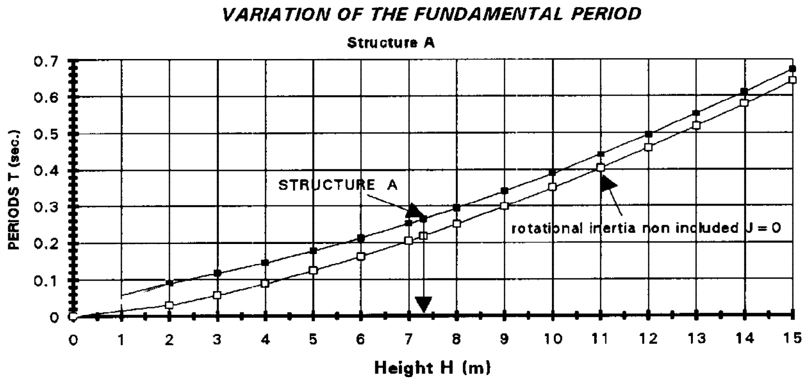


Fig. 5. Variation of the fundamental period considering the rotational inertia effect.

Non-linear analysis

In this section, the numerical results of the non-linear analysis are shown. The three ground motion records (see fig. 3) are used to study the seismic response of the structures A and B. The analysis model was made considering a rigid foundation and the rotational inertia effect at the top of the pier.

Table 6. Comparison of the fundamental period respect to elastic model.

	Non-linear analysis	Elastic model			
Structure	T_{nl}	T_C	T_e	T_{nl} / T_c	T_{nl} / T_e
A	0.288	0.264	0.203	1.09	1.41
B	0.626	0.6145	0.50	1.02	1.25

This difference is because of: non-linear behavior and the contribution of the rocking of the girder at the top of the pier.

Structure A.

Figures 6.a to 6.b show the seismic response of the structure A analyzed to the Unión.ns record at the Guerrero coast. The maximum base shear (fig. 6.a) is about 1.1W of the total weight, and the shearing force capacity of the column is not exceeded, warranting bending behavior. Drift history of the bridge is lower than the limit recommended in RDF building code 0.006H. Hysteresis loops (fig. 6.c) show an elastic-linear response without energy dissipation. The ductility demand remains in the elastic range. However, this structure is more excited for the Unión.ns record of the Pacific coast, containing a high frequency (rock site) with a dominant period about the 0.7 seconds. In figures 6.d and 6.e, it can be seen, the comparison of the seismic response of the head rocking moment M_c toward overturning moment M_b, the average ratio M_c / M_b is about of the 24%.

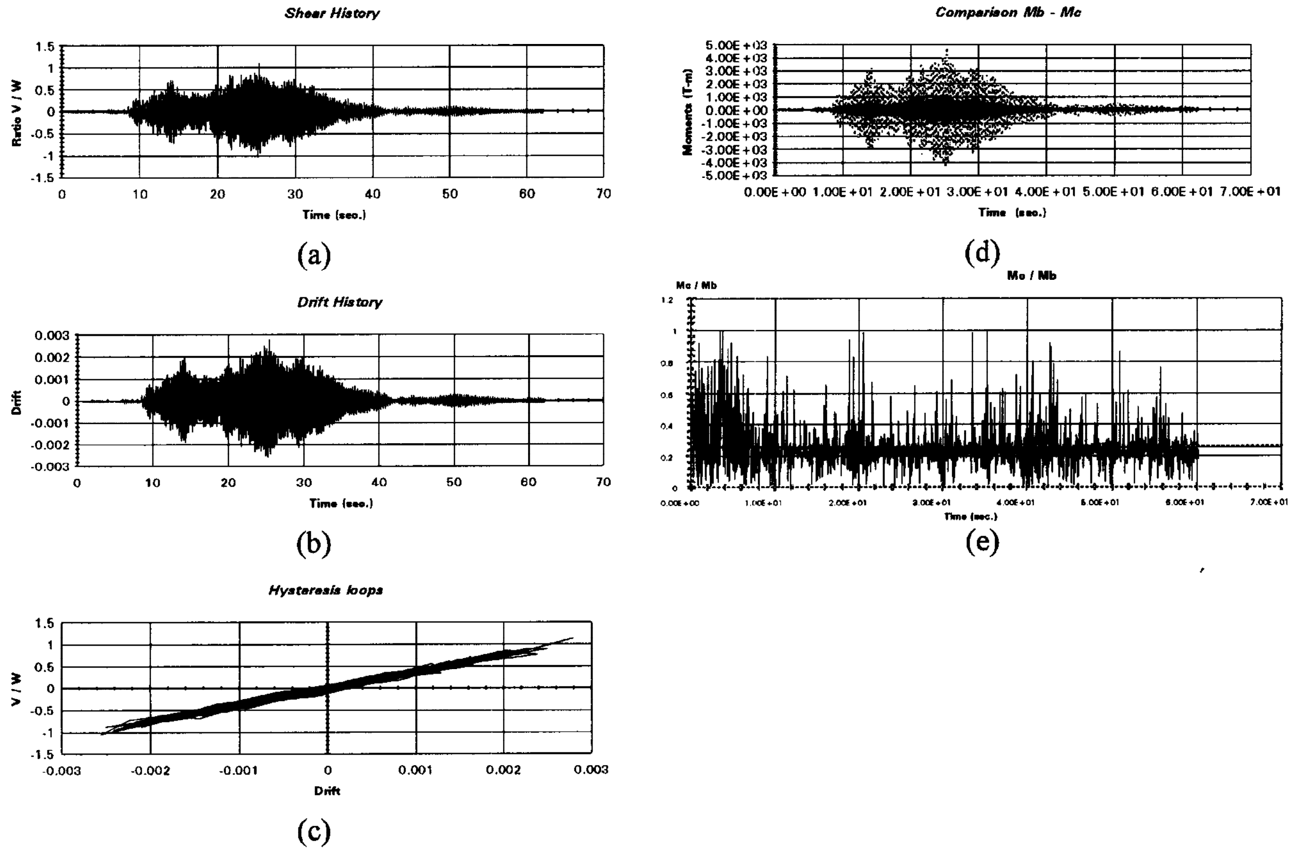


Fig. 6. Seismic response of Structure A with T_1 = 0.28 sec.

Concerning to the other two accelerograms (SCT.ew and Viveros.ew) recorded in Mexico City, the seismic responses of the structure are lower than Unión.ns record, remaining the ductility demands in the elastic range. However, the average ratio M_c / M_b is about 18% for two cases (see table 7).

Table 7.

Ground motion record	Ductility demand $\mu_\Delta = \Delta_{max} / \Delta_y$	M_c/M_b
Unión.ns	1	0.24
SCT.ew	< 1	0.17
Viveros.ew	< 1	0.18

Structure B.

In figures 7.a to 7.d, the numerical results of the seismic response are summarized, using the Unión.ns record. Similar pattern behavior of the structure A being observed in the structure B. The maximum base shear is about 0.48W of the total weight, this base shear represents 83% of the shearing capacity of the column. The structural behavior is a bending behavior without problems by shearing failure at the bottom of the pier. The maximum drift is about 0.0028H, lower than the limit recommended by the RDF building code. The hysteresis loops show a non-linear seismic response, with a light variation on the loop ways. This variation is due to the rocking of the bridge deck. The ductility demand is $\mu_\Delta = \Delta_{max} / \Delta_y = 1.1$, without showing an important structural damage at the base of the pier. However, it can be seen with a little ductility demand, the element is near to the shearing capacity limit. Figures 6.d and 6.e show the history bending moments at the top and the bottom of the pier, the average ratio is about 0.29%, this ratio is upper than the obtained in the structure A. This increase is due to a major mass of the bridge deck and at the height.

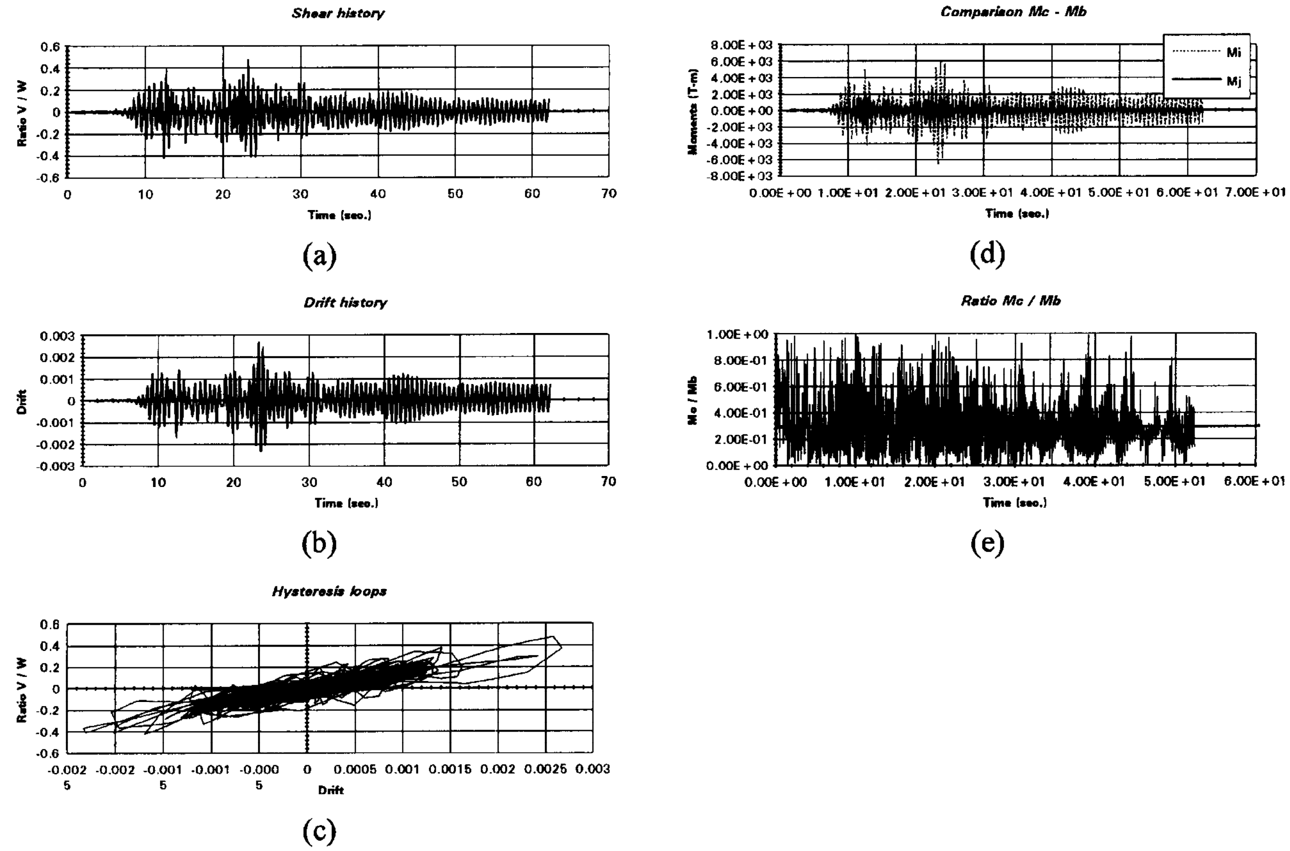


Fig. 7. Seismic response of Structure B with $T_1 = 0.626$ sec.

For the cases when the structure is analyzed for the SCT and Viveros records, the seismic responses are linear, and the drift history is lower than the limit recommended (see table 8).

Table 8.

Ground motion record	Ductility demand $\mu_\Delta = \frac{\Delta_{max}}{\Delta_y}$	M_c/M_b
Unión.ns	1.1	0.29
SCT.ew	elastic range	0.25
Viveros.ew	elastic range	0.28

CONCLUSIONS

Commentary and conclusions

In this work, the behavior and seismic response of two typical structures (bridge) of reinforced concrete has been studied, in order to assess the ductility demand, taking into a count in the dynamic behavior the rotational inertia.

In the first part is carried out the response spectra elastic analysis, which is compared with the static method, using the design response spectra recommended by the RDF Mexican Building code (RDF, 1990), and considering the seismic coefficients for the geotechnical zones (I, II and III) firm, transition and soft soils, trying to estimate the head rocking moment M_c at the top of the pier toward overturning moment M_b. The ratio M_c/M_b fluctuates about from 25 to 30% for the structure A, and 28 to 33% for the structure B.

It can be seen, that, the rotational inertia effect at the top of the column, plays an important role on the inelastic seismic response of bridge piers.

In the second part of this research the non-linear step-by-step analyses are carried out on the two structures using three seismic records occurred in the Pacific coast, in September 19, 1985. The two structures were analyzed considering a rigid foundation, in order to study the seismic response and comparing the results. These results have shown for structure A a linear behavior without damage and the ductility demand remained in the elastic range. This behavior is due to a very rigid structure with a short period T = 0.25 seconds. However, the ratio M_c/M_b is about from 17 to 24% for all cases. Results obtained of the analysis of the structure B show a non-linear behavior using the Unión.ns accelerogram recorded in Guerrero coast with a ductility demand about 1.1. Respect to the accelerograms recorded in the Valley of Mexico City, the response of the bridge is linear and the ductility demand remained in the elastic range. The influence of the rotational inertia was superior in relation to the structure A. This difference is due to a major mass **m** concentrated in the top of the pier with more rotational inertia **J**.

The ductility demands about the displacement remain in the linear behavior, in most the cases. However, this structures with a short period are more excited, when the ground motion records containing a high frequencies and the ductility demands are increased, showing an inelastic seismic response.

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