SEISMIC VULNERABILITY EVALUATION OF RC URBAN BRIDGES

Darío Rivera Vargas[1]

[1] *Center of Multidisciplinary Research, Campus Acatlán, National University of Mexico (UNAM), Mexico*
Email:dario.arna@hotmail.com

ABSTRACT:

A methodology to evaluate the seismic vulnerability of reinforced concrete (RC) urban bridges is presented. The objective of this paper resides in outlining a methodology to derive vulnerability functions for different typologies of urban bridges, which can relate the seismic hazard and the structure physical damage. This methodology doesn't take in consideration the effects of soil-structure interaction. It's concluded, among other things, that the developed methodology will be of great utility to assess the structural safety degree of the urban bridges before the seismic action, with the smallest number possible of field data to simplify the seismic vulnerability evaluation of RC bridges.

KEYWORDS: Urban Bridges, Seismic Vulnerability, Physical Damage Index

1. INTRODUCTION

In Mexico has not been given priority to the investigation on the bridges seismic behavior as has been devoted to the buildings, for this reason a common established practice doesn't exist in the seismic design of bridges, so there isn't a specific national code. The above-mentioned represents a risk for the population when not being possible to define the level of security that keep these bridges before the action of the earthquake, which are vital for the communication and that its failure or bad operation generate collateral damages to the population, such as: traffic problems and economic losses for several sectors of the society.

During the occurrence of earthquakes relatively recent in Mexico, such as: Tehuacán (1999), Oaxaca (1999) and Tecomán (2003), in the sector communications and transports, the damages in bridges have had a strong socio-economic impact, even without arriving to the collapse by the ground shaking. The above-mentioned to make notice that for a damage level that implies the collapse of the bridges, scenarios of more impact can be had those happened until the moment, just as it has happened in other parts of the world, and more even, if it's took in consideration that the number of bridges has grown in the main cities from Mexico, recently.

The objective of this work resided in outlining a methodology to evaluate the seismic vulnerability of RC urban bridges, by means of the construction of vulnerability functions for different typologies of urban bridges of simple geometry, that is to say, straight bridges, lightly skewed (smaller angle at 15º), without abrupt variations of mass and stiffness, and similar span lengths. In this investigation didn't take into account the effects of soil-structure interaction.

2. APPROACHES TO EVALUATE THE SEISMIC VULNERABILITY OF URBAN BRIDGES

There isn't a statistical database on damages to bridges, with wide intervals of parameter's values that define their basic properties (stiffness and strength), before earthquakes of diverse intensities, in order to obtain in a reliable way its semi-empiric vulnerability functions. For lack of this information, the estimation of these functions has to be on models of the structures dynamic response, just as it is commented in the following.

2.1 Damage type

Before the action of the earthquake the bridges can experience damages in the substructure: flexure-shear cracks, concrete spalling, failure of longitudinal reinforcement or of stirrup. In a same way damages can be presented in the superstructure: pounding of decks and relative displacement between decks.

For effects of this studying it will become special attention in the columns physical damage by be considered this structural element the most important in the bridges global behavior; observations carried out in bridges damaged in other countries during the occurrence of strong earthquakes, San Fernando (1971), Kobe (1995), among others, revealed that the bridges failure was due to a bad behavior of their columns (figure 1).

Figure 1 Damages observed to bridges (Riobóo, 2005)

2.2 Approaches to evaluate the physical damage

Two forms exist to estimate the bridges damage caused by earthquake. (1) Evidences physics: it can be obtained of bridges that were damaged before real earthquakes or of experimental results, for example, a bridge column tested in laboratory to reproduce the behavior observed during an earthquake. (2) Analytic models: with these it is looked for to estimate the structural dynamic response of bridges and to relate it with certain damage levels. In this work the combination of experimental results on laboratory tests and theoretical models was used.

2.3 Analytic prediction of lateral displacement capacity of columns

In Rivera's work (2005) equations were deduced to evaluate the capacity of yielding drift, γ_y. For columns in cantilever the following expressions can be used:

$$\gamma_y = \frac{1}{3}\phi_y H \tag{2.1}$$

rectangular section: $$\phi_y = 3.75\frac{\varepsilon_y}{h_c}(0.30 + 10.50\rho_l - 125\rho_l^2) \tag{2.2}$$

circular section: $$\phi_y = 3.75\frac{\varepsilon_y}{D}(0.30 + 11.20\rho_l - 146\rho_l^2) \tag{2.3}$$

where, H is the height of the bridge column, ρ_l is the ratio of longitudinal reinforcement, hc and D is the depth and the diameter of cross section, respectively, ε_y is the yielding deformation of the reinforcement steel and φ_y is the yielding curvature.

The capacity of ultimate drift, γ_u, can be estimated with the equation derived for columns in cantilever given by:

$$\gamma_u(\%) = \beta_0 + \lambda_e \frac{f_{yt}}{14 f'_c}\left(\beta_1 + \beta_2 \frac{P}{A_g f'_c}\right) + \beta_3\left(\frac{P}{A_g f'_c}\right) \tag{2.4}$$

rectangular section: $\lambda_e = k_e \rho_s$ (2.5)

circular section: $\lambda_e = \rho_{st}$ (2.6)

where, γ_u (%) is ultimate drift capacity (in percentage), P/Agf'c is the vertical load ratio, as a percentage of compressive strength of concrete core (the ratio multiplies by 100), λ_e is the effective confinement, ke is a confinement effectiveness coefficient (Mander *et al*, 1988), and f_{yt} yielding strength of the traverse reinforcement.

The constants of the equation 2.4 are evaluated in function from the axial load to which is subjected the column and of their aspect ratio (limited to values between 3 and 6) by means of the expressions that are shown in the table 1. The variation coefficient of the equation 2.4 regarding experimental results is of 0.31, what shows a grade of acceptable approach (Rivera, 2005).

Table 1 Values of beta (β)

Coefficients	Rectangular Section		Circular Section	
	P/Agf'c <15%	15%≤P/Agf'c≤20%	P/Agf'c <15%	15%≤P/Agf'c≤20%
β0	$4.64-0.38\frac{H}{L}$	$0.22\frac{H}{L}-0.75$	$3.30-0.27\frac{H}{D}$	$0.70\frac{H}{D}-3.68$
β1	$453.90+46.50\frac{H}{L}$	$1280.70-18.50\frac{H}{L}$	$453.90+46.50\frac{H}{D}$	$316.69+189.98\frac{H}{D}$
β2	$14.58-5.71\frac{H}{L}$	$0.75\frac{H}{L}-49.40$	$14.58-5.71\frac{H}{D}$	$-\left(0.38+7.15\frac{H}{D}\right)$
β3	$0.0422\frac{H}{L}-0.37$	$0.0165-0.00078\frac{H}{L}$	$0.0422\frac{H}{D}-0.37$	$0.097-0.02\frac{H}{D}$

Note: L and D are the depth (parallel to the action of the earthquake) and D the diameter of the cross section, respectively

To calculate the yielding force (Vy) the following expression is used

$$V_y = K_{cr}\gamma_y H \tag{2.7}$$

where, K_{cr} is the cracked stiffness to flexion until the yielding point of the element. To obtain the cracked-section moment of inertia (I_{cr}) the following expressions can be used (Rivera, 2005):

rectangular section: $$\frac{I_{cr}}{I_g} = 0.19 + 11.60\rho_l + 0.012\frac{P}{A_g f'c} - 0.17\rho_l\frac{P}{A_g f'c} \tag{2.8}$$

circular section: $$\frac{I_{cr}}{I_g} = 0.22 + 13.44\rho_l + 0.011\frac{P}{A_g f_c'} - 0.16\rho_l\frac{P}{A_g f_c'} \tag{2.9}$$

where, I_g represents the gross section moment of inertia; the value of P/Agf'c multiplies by 100.

2.4 Estimation of seismic demands

In the construction of the vulnerability functions it is common to use the acceleration like a parameter in the estimation of structures seismic demand and by means of which is looked for to relate it with the damage level of the bridge, in such a way that is obtained the accelerations that give place to the beginning of damage and structure failure. The first damage level can be evaluated directly of the elastic spectrum, as long as that for the damage level in that the structure has an inelastic behavior, it is pertinent to use approximate methods that can take in consideration this effect in the structure seismic response.

Inside the approximate methods to estimate the no-lineal seismic response are those based on strength-reduction coefficient R_μ, that represents the reduction of structure lateral strength (or acceleration) due to the no-lineal behavior. In the part of methodology, the expressions that are recommended to calculate R_μ for different soils types are described

3. METHODOLOGY

3.1 Basic information

During a field inspection it is possible to obtain basic information to analyze the seismic vulnerability of urban bridges, just as: structural configuration of the bridge, that is to say, if it is a bridge with single-column bents or multicolumn bents in the traverse direction; height of the bridge columns (H); diameter of circular cross section (D), base and depth of the rectangular cross section (b x L); and design code used or year of construction.

Sometimes is difficult to know specific and detail information, as compressive strength of concrete (f'_c) and yield stress of reinforcement (f_y,), for solve this situation, it's possible to suppose conservative values according to the design practice in Mexico: f'_c = 20 MPa and f_y = 400 MPa, with ε_y= 0.0019. For the case of having an estimate of the axial load on the columns (W_c), can be considered a value average $W_c = 0.1f'_cA_g$ (Wehbe *et al*, 1996), although in the case of bridges with single-column bents can be $W_c = 0.15f'_cA_g$. In what concerns to ratio of longitudinal reinforcement (ρ_l) can be supposed a conservative value of 0.02. While for ratio of traverse reinforcement (ρ_t, λ_e) can be supposed with base in the year of bridge construction (table 2).

Table 2 Ratio of traverse reinforcement or confinement that can be supposed for different years of construction

Year of bridge construction	Confinement Reinforcement	
	Circular cross section	Rectangular cross section
Before of 1972	ρ_t =0.0015	ρ_t =0.0015 λ_e=0.0007
between 1972 and 1992	ρ_t =0.005	ρ_t =0.005 λ_e=0.003
After of 1992	ρ_t =0.007	ρ_t =0.007 λ_e=0.005

3.2 Procedure

1. Calculation of yielding drift (γ_y). For the case of a single-column in cantilever the equation 2.1 is used. For multicolumn bents (supposing the deck as rigid diaphragm) can be calculated with the following equation:

$$\gamma_y = \frac{1}{6}\phi_y H \tag{3.1}$$

2. Calculation of ultimate drift (γ_u). This parameter is calculated with the equation 2.4. Due to the uncertainty that keeps this equation regarding the prediction of lateral displacement capacity, it is recommended that the drift value obtained must be multiplied by a factor of 0.8; for be of conservative side.

3. Obtaining of ductility lateral displacement (μ)

$$\mu = \frac{\gamma_u}{\gamma_y} \tag{3.2}$$

4. Obtaining of period of structure vibration (T_{cr})

5. Estimate of yielding lateral force (V_y). It is calculated with the equation 2.7.

6. Evaluation of R_μ. For a damping ratio of 0.05 the equations are the followings (Arroyo and Terán, 2002):

Stiff soil

$$R_\mu = (1.11\mu - 1.0119)\left(\frac{T_{cr}^{\ 1.2}}{0.002 + T_{cr}^{\ 1.2}}\right) + 1 \tag{3.3}$$

Soft soil

$$R_\mu = \frac{\left(\frac{T_{cr}}{T_g}\right)^\theta}{0.175 + \left|\frac{T_{cr}}{T_g} - 1\right|}(0.5529\mu - 0.55) + 1 \tag{3.4}$$

$$\theta = \frac{\mu^4}{2.5 + \mu^4} \tag{3.5}$$

where, T_g is the period of ground where the bridge is located.

7. Calculation of spectral accelerations (Sa). Acceleration that begins damage (slight cracking when it begins to yield the longitudinal reinforcement), Sa_y

$$Sa_y = \frac{V_y}{W_T} g \tag{3.6}$$

Acceleration that cause the column failure, Sa_u

$$Sa_u = \frac{V_y}{W_T} R_\mu g \tag{3.7}$$

where, W_T is the total weight of bridge tributary area in analysis and g is the gravity acceleration.

8. Deduction of vulnerability function. In the deduction of the function of physical damage index (I_{DF}), denominated in this work as vulnerability function, it's take in consideration two basic points of function curve: beginning of damage and near of the failure, with this points the parameters are obtained *a* and *m* corresponding to the vulnerability function given by:

$$I_{DF}(Sa_i) = 1 - e^{-au^m} \tag{3.8}$$

$$u = \frac{Sa_i}{Sa_u} \tag{3.9}$$

$$m = \frac{-5.69734}{\ln\left(\frac{Sa_y}{Sa_{pu}}\right)} \quad (3.10)$$

$$a = \frac{\ln(0.99)}{\left(\frac{Sa_y}{Sa_u}\right)^m} \quad (3.11)$$

where, Sa_i is the demanded acceleration in the bridge and for which is wanted to know its vulnerability grade, and $Sa_{pu} = 0.95Sa_u$.

An interpretation of physical damage index (I_{DF}) was proposed with base in works that have studied the relationship between the structure response and their respective damage level (Rivera, 2005; Karim and Yamazaki, 2001). In the table 3 a range of values of I_{DF} associated to a damage level and to a vulnerability grade is presented.

Table 3 Interpretation of I_{DF}

I_{DF}	Damage level	Vulnerability
$0<I_{DF}<0.05$	Null	Very low
$0.05\leq I_{DF}\leq 0.15$	Almost null	Low
$0.15<I_{DF}\leq 0.40$	Moderate	Medium
$0.40<I_{DF}<0.95$	Severe	Height
$0.95\leq I_{DF}$	Full	Very height

4. APLICATION

With this methodology a catalog of vulnerability functions was elaborated, with which can be obtained the values of *m, a,* Sa_u/g and T_{cr} to evaluate the physical damage index of two bridges types, in the table 4 some cases are shown, but in Rivera's work (2007) the complete catalog of vulnerability functions is presented.

Table 4 Bridges located in stiff soil

Column cross section	Year of bridge construction	H/D (ó H/L)	m	a	Sa_u/g	T_{cr} (s)
Rectangular $1\leq L/b\leq 1.25$ Bridges with Single-column bents	Before of 1972	3	12.994	5.834	0.35	0.49
		4	13.422	5.963	0.26	0.75
		5	13.699	6.049	0.20	1.05
		6	13.893	6.109	0.17	1.38
	Between 1972 and 1992	3	3.277	3.544	1.30	0.49
		4	3.736	3.628	0.78	0.75
		5	4.158	3.707	0.53	1.05
		6	4.552	3.783	0.39	1.38
Circular Bridges with multicolumns bents	Alter of 1992	3	2.243	3.361	5.52	0.46
		4	2.519	3.408	3.07	0.71
		5	2.783	3.455	1.94	1.00
		6	3.042	3.501	1.33	1.32

As application example using the table 4, it is required to evaluate the grade of seismic vulnerability of two fictitious urban bridges, supposing that they are located in Colima, Mexico. The structural configuration of both bridges is similar in the longitudinal direction, but not in the traverse direction, just as it is shown in the figure 2. It is considered that the ground type is a stiff soil. Of the visit to the place where the bridges are located, the information obtained is reported in the table 5.

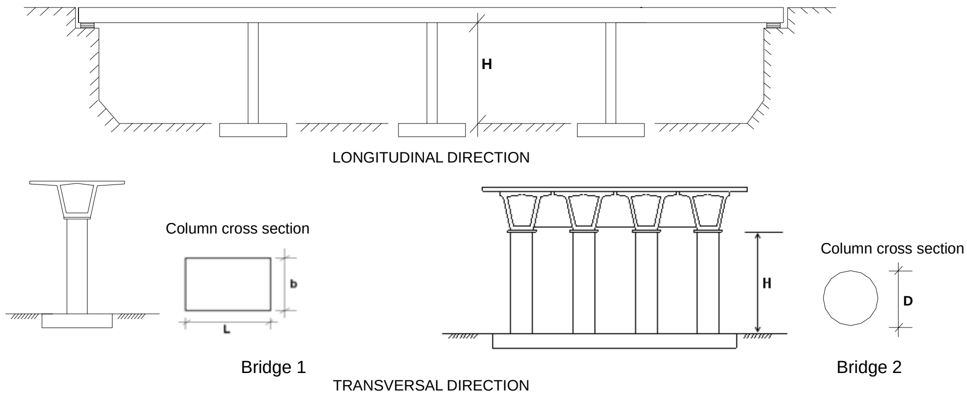

Figure 2 Structure configuration of the bridges

Table 5 Dates of the bridges

Bridge	Column cross section	Section dimentions (mm)	Column height, H (mm)	Aspect Ratio	Year of bridge Construction
1	Rectangular	B=1000 L=1250	6250	H/L=5	Between 1972 and 1992
2	Circular	D=1000	8000	H/2D=4	Alter of 1992

With the information of the table 5 the catalog of vulnerability functions is consulted (table 4) to obtain the parameters values of the vulnerability function of each bridge (table 6). Substituting these values in the equation 3.8 are obtained the curves shown in the figure 3.

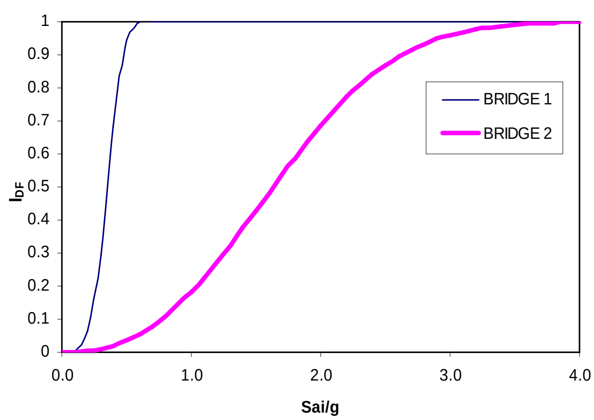

Figure 3 Vulnerability functions of each bridges

To evaluate the acceleration demands (Sa_i/g) of each bridge the design spectra of CFE handbook (1993) was used, considering that Colima is located in the seismic area D (high seismicity) and that the bridges are located in stiff soil. When substituting the values of Sa_i/g in the vulnerability functions of the bridges 1 and 2, it is obtained the I_{DF}, damage and vulnerability level of each bridge (table 6).

Table 6 Evaluation of damage and vulnerability level

Bridge	m	a	Sa_u/g	T_{cr} (s)	Sa_i/g CFE (1993)	I_{DF}	Damage	Vulnerability
1	4.158	3.707	0.53	1.05	0.57	0.95	Severe	Height
2	2.519	3.408	3.07	0.71	0.69	0.076	Almost null	Low

5. CONCLUSIONS

In this paper the approaches to evaluate the seismic vulnerability of RC urban bridges were presented. With base in the combination of analytic procedures and experimental results a methodology was developed to derive vulnerability functions for different typologies of urban bridges, putting special attention in the physical damage of columns, since the bridge columns are fundamental part of the structure global stability.

The developed methodology will be of great utility to assess the structural safety degree of the urban bridges before the seismic action, with the smallest number possible of field data to simplify the seismic vulnerability evaluation of RC bridges. This methodology will allow to the authorities of Disaster Prevention and institutions related with the bridges design and construction to identify those of high risk in order to avoid possible collateral damages to the population. However, in the future it will be necessary to continue improving the prediction of the lateral deformation capacity of columns, as well as the estimate of the seismic demand, to reduce the uncertainty in the diagnosis of the damages scenario that can experience the bridges before eventual earthquake excitations.

ACKNOWLEDGMENTS

It is appreciated to the National Center of Disaster Prevention (CENAPRED) the support received for the development of this research.

REFERENCES

Arroyo D. y Terán A. (2002). Factores de Reducción de Fuerzas Sísmicas para el Diseño de Estructuras con Sistemas Pasivos de Disipación de Energía. *Revista de Ingeniería Sísmica,* No. 66, pp. 73-93.

CFE (1993). Manual de Diseño de Obras Civiles. Diseño por Sismo, Comisión Federal de Electricidad, Instituto de Investigaciones Eléctricas, pp. 1.3.26-1.3.29.

Karim K. R. and Yamazaki F. (2001). Effect of Earthquake Ground Motions on Fragility Curves of Highway Bridge Piers Base on Numerical Simulation. *Earthquake Engineering and Structural Dynamics*, 30.

Mander J. B., Priestley M.J. N. and Park R. (988). Theoretical stress – strain model for confined concrete. *Journal of the Structural Division, ASCE,* Vol. 114, No. 8, pp. 1804-1826.

Rivera D. (2005). Seismic Design of RC Urban Bridge Columns in the Mexico City, Ph. D. Thesis, National University of Mexico, UNAM, pp. 87-100. (In spanish).

Rivera D. (2007). Simplified Evaluation of Seismic Vulnerability of Urban Bridges, Research Report, Number 51, National Center of Disaster Prevention, CENAPRED, pp. 41-45. (In spanish).

Wehbe N., Saiidi M., Sanders D. y Douglas B. (1996). Ductility of Rectangular Reinforced Concrete Bridge Columns with Moderate Confinement, Technical Report NCEER-96-003.