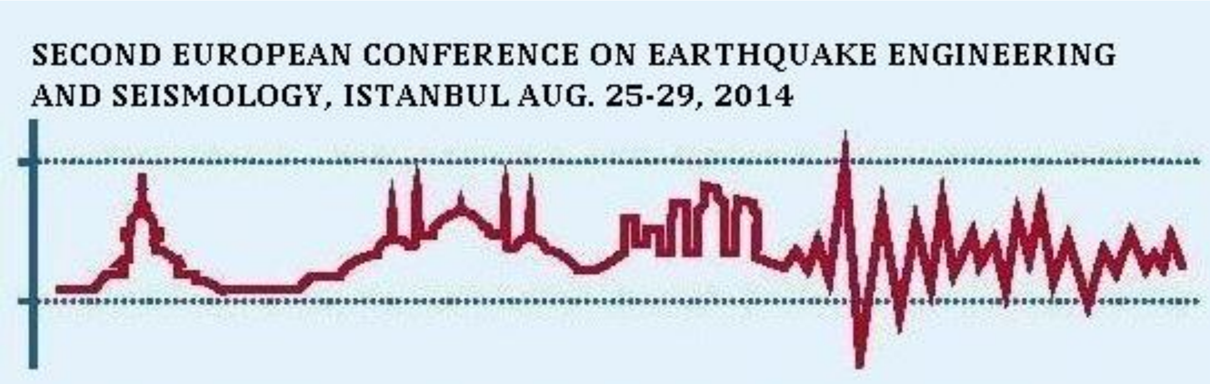

SEISMIC VULNERABILITY ASSESSMENT USING AMBIENT VIBRATIONS ON BUILDINGS IN CENTRAL MEXICO

Eduardo ISMAEL[1], J Alberto HERRERA[2], Antonio HERRERA[2], Danya I MORA[2], Arnold CASTILLO[2] and Miguel A FLORES[3]

ABSTRACT

Two procedures for estimating the seismic vulnerability for existing buildings in Central Mexico using ambient vibration records are presented. The vulnerability is estimated in terms of a reliability measure. The reliability analysis is carried out using analytical models which provide the linear and non-linear responses. The dynamic properties of those models are calibrated from experimental analysis considering ambient vibrations of the buildings. The simplified procedure, using linear responses, employs a safety factor. The detailed procedure, using the non-linear responses, employs a damage index defined as the Secant Stiffness Reduction Index (I_{SSR}); here the capacity measure of the structural systems is estimated from the pushover analysis. In order to illustrate the procedures, two buildings, both in central Mexico, were analysed, one of them was a reinforced concrete school building that belongs to the infrastructure of the UPAEP University and is located in Puebla; another one is a precast concrete Hospital building located in Tlaxcala.

INTRODUCTION

Considering the impact of earthquakes on society (loss of life and property), the importance of mitigating the seismic risk has been recognized around the world. A strategy for mitigating this risk is to have buildings that can withstand the effects brought about the earthquakes. To avoid or reduce the consequences or the amount of damage caused by these events, the earthquake engineering provides criteria, methods and tools for structural design of such infrastructure, as well as testing, maintenance and reinforcement, if necessary, of existing buildings. Moreover, the margin of uncertainty that affect our ability to predict and characterize seismic intensity level is very high. This uncertainty affects our understanding of the relationship between the actual properties of the constructions (gravitational loads, stiffness and mechanical properties of the structure) and the assumed values in the structural design process. Rigorously, the above forces deal with these concepts within a framework based on probability analysis applied to seismic risk estimation. This should develop procedures for estimating the structural vulnerability level of existing buildings, which should be useful to propose rehabilitation strategies to reduce the seismic risk.

On the other hand, displacement-based criteria for earthquake resistant designs are based on the concept that the event of reaching a given performance limit is associated with the condition that the structural distortion reaches a value equal to the corresponding deformation capacity. According to

[1]Professor, Civil Engineering School, UPAEP, Puebla, Mexico, eduardo.ismael@upaep.mx
[2]Undergraduate Student, Cıvıl Engineerig School, UPAEP, Puebla, Mexico; josealberto.herrera@upaep.edu.mx, antonio.herrera@upaep.edu.mx, danyaivvone.mora@upaep.edu.mx, arnold.castillo@upaep.edu.mx
[3]Civil Engineer, Local Society of Civil Engineers (CICET AC), Tlaxcala, Mexico, mikefe@hotmail.com

this, the estimation of the seismic reliability of complex nonlinear systems for given values of the ground-motion intensity is ordinarily based on a measure of the probability that, for an ensemble of earthquake excitations with a specified intensity, the ratio of the peak absolute value of the nonlinear displacement response demand of the system to the corresponding deformation capacity is greater than unity (Esteva et al. 2010).

The possibility of estimating the seismic reliability function for a structural system, in terms of a probabilistic description of the reduction in secant lateral stiffness for the maximum amplitude of the response of the system to an earthquake ground motion of specified intensity, was first proposed by Esteva and Ismael (2003) and further refined by Esteva and Díaz-López (2006).

In this paper two approaches for seismic vulnerability assessment on buildings in Central Mexico are presented. The procedures consider the estimation of the linear and non-linear responses using structural models. Some dynamic properties of those models are calibrated from experimental analysis considering ambient vibrations of the buildings. For describing the structural vulnerability we use two procedures. One of them based on a safety factor and another based on a damage index defined as the Secant Stiffness Reduction Index (I_{SSR}). The latter procedure considers that the capacity measure of the structural systems is estimated from the pushover analysis. In order to illustrate the procedure two buildings, both in central Mexico, were analysed. One of them is a reinforced concrete School building located in Puebla; and another is a precast concrete Hospital building located in Tlaxcala. In this study we are interested in those buildings because according to the structural regulations in Mexico these buildings belong to group A and being considered important, so after a seismic event they must maintain appropriate security levels.

SIMPLIFIED APPROACH FOR SEISMIC VULNERABILITY ASSESEMENT

The seismic vulnerability functions are quantitative relationships between several indicators of the expected damage on the building and the seismic intensity measure. In this study we are interested on the security level with respect to the possible collapse of the building, in this way the vulnerability function can be expressed in terms of failure probability conditional to the occurrence of an earthquake of a given intensity. There are different criteria to estimate the reliability functions; the Cornell´s reliability index (Cornell, 1969) is very popular around the world. Unfortunately, to estimate the Cornell´s index in an existing building is very difficult because we need to define information that is not always available.

Given the above, in this paper we propose the use of a safety factor in order to estimate a preliminary reliability level of existing buildings. The safety factor is defined as follows:

$$Z(y) = \frac{V_{bR}}{V_b(y)} \tag{1}$$

In Eq. (1) V_{bR} is the resistant base shear on the building (lateral capacity force), $V_b(y)$ is the demand of base shear force acting on the building given a seismic intensity y. It is important to mention that the failure criterion is when $Z(y)$ is less than unity.

In order to determine the value of V_{bR} we can make use of the available information of the structural system (plans, structural details, calculation memory, etc.) and the design criteria regulations that can be applied.

DETAILED APPROACH FOR SEISMIC VULNERABILITY ASSESEMENT USING A DAMAGE INDEX, I_{SSR}

This criterion is based on adopting a fault condition in terms of a damage index, I_{SSR}, it considers that the reliability of the system is referred to the collapse. The I_{SSR} value can be determined if the following equation applies:

$$I_{SSR} = \frac{(K_0 - K)}{K_0} \tag{2}$$

Here $K=V_b/X_N$ is defined as the value of the reduced secant stiffness of a nonlinear system at the instant that the overall lateral displacement, X_N, reaches its maximum absolute value in response to a seismic excitation; V_b is the base shear at the same instant that the maximum response occurs. K_0 is the value that K acquires when the response is linear were its value is obtained from pushover analysis in this study. For a given seismic intensity, if $I_{SSR} < 1.0$ the structural system maintain a survival condition, on the other hand if $I_{SSR} = 1.0$ the condition leads to collapse of the structure.

LINEAR AND NON-LINEAR RESPONSES

Analysis of linear response

Ismael et al. (2012) present the criteria for estimating the linear responses of existing buildings. In order to determine the linear responses a structural model for each building is developed using the software SAP2000 v.14.1. To assign and calibrate the properties of the models we obtain ambient vibration records in order to estimate the vibration periods and frequencies of the first three modes of the building. In the next section a description of the procedure is presented.

Estimation of the frequencies on the building

Ambient vibration records in three points were obtained on the building, P01 and P02 which correspond to the geometric centroid and the corner at the roof of the building, respectively; P03 corresponds to the geometric centroid at the ground floor of the building. For each point four records were taken considering 15 minutes. A triaxial accelerometer was used as instrument for obtaining the records.

Frequencies and periods were determined for the first three modes of vibration of the building: longitudinal mode (L), transversal mode (T) and rotational mode (R). For this, a computer program GEOPSY (Wathelet, 2005) was used in order to obtain the Amplitude Fourier Spectrum (AFS) for each record, in this way, the horizontal components of the movement (longitudinal and transversal) are only considered for computing the spectral ratios. The procedure for each of the mode is described below. Longitudinal mode (L), the numerator corresponds to the AFS in the longitudinal component obtained in the geometrical centroid at the roof level, and the denominator corresponds to the AFS in the longitudinal component obtained in the geometrical centroid at the ground floor. Transversal mode (T), the numerator corresponds to the AFS in the transversal component obtained in the geometrical centroid at the roof level, and the denominator corresponds to the AFS in the transversal component obtained in the geometrical centroid at the ground floor. Rotational mode (R), the numerator corresponds to the AFS in the transversal component obtained in the corner at the roof level, and the denominator corresponds to the AFS in the transversal component obtained in the geometrical centroid at the same level.

Analysis of non-linear response

Pushover analysis

To determine the I_{SSR} it is necessary to obtain the pseudo-static non-linear response (pushover analysis) of the structural model that corresponds to a multiple degrees of freedom system. In order to carry out the pushover analysis a two dimensional structural model is subjected, at its base, to a monotonic acceleration that grows linearly with time. The growth rate of acceleration is taken low enough to avoid the occurrence of vibrations. As a result the structure is deformed by inertial effects alone. Uncertainties in the values of the gravitational loads and geometric properties are considered, and for the pushover analysis these parameters correspond to their expected values. The lateral configuration in the model is obtained by applying a mass distribution model which corresponds to the first mode.

From this analysis we obtain a curve that relates the shear base, V_b, with the global lateral displacement at the roof of the system, X_N. Apart from these curves, the pushover analysis provides a series of lateral configurations of the displacements in different levels and response values at each instant of interest. Pushover analysis also provides the estimation of the deformation capacity, u_F, of the structural system. In this paper the criterion for estimating the deformation capacity corresponds to a 20% reduction of the peak shear value.

Dynamic non-linear analysis

The estimation of non-linear responses was carried out using step by step analysis of same structural modes described in above section; we also considered the uncertainties in the structural properties and for different seismic excitations. For this analysis the computer program DEIH was used, which is a modified version of DRAIN-2D (Powell, 1973). If it is a representative sample of the resulting responses, one can determine the probability distribution of the response; such distribution is characterized by the expected value of response and the corresponding range in terms of intensity.

In order to estimate the structural reliability, a probabilistic model of the mechanical properties and the gravitational loads acting on the system were formulated, and a sample of possible realizations of the vector of those properties were generated by Monte Carlo simulation, as described by Esteva et al (2002), using the statistical properties reported by Meli (1976) and Mirza and McGregor (1979). The model proposed by Wang and Shah (1987) was adopted to represent the constitutive functions describing the bending behaviour of the critical sections at the ends of beams and columns. For each system in the sample, a nonlinear analysis was made of its response to a randomly chosen member of a sample of actual ground motion time histories representative of those expected at the site of interest.

Seismic excitation

For the non-linear analysis the seismic excitation used in this paper corresponds to the earthquake occurred on 20th March 2012 in the coast of Guerrero State in Mexico. The table 1 shows the main parameters for this event. The earthquake was recorded by the local seismic network of the UPAEP University, the accelerogram employed to carry out the dynamic non-linear analysis corresponds to the N-S component which presented the maximum values of ground acceleration.

Table 1. Main parameters of the earthquake recorded in the station located in the Campus Central, UPAEP

DATE	TIME	LATITUDE	LONGITUDE	DEEP (Km)	Mw	PGA N-S (cm/sec^2)	PGA E-W (cm/sec^2)	PGA V (cm/sec^2)
20/03/2012	12:02	16.251	-98.521	16	7.4	18.84	12.33	7.64

Figures 1 and 2 show respectively the ground motion time history and the pseudo-acceleration response spectrum (with damping ratio equal to 0.05) used in the non-linear analysis.

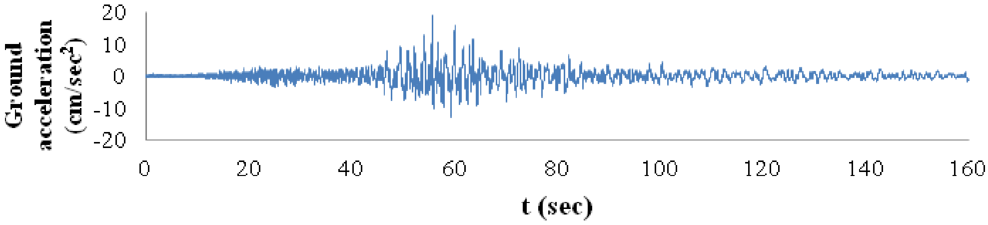

Figure 1. Ground motion time history used for dynamic non-linear analysis

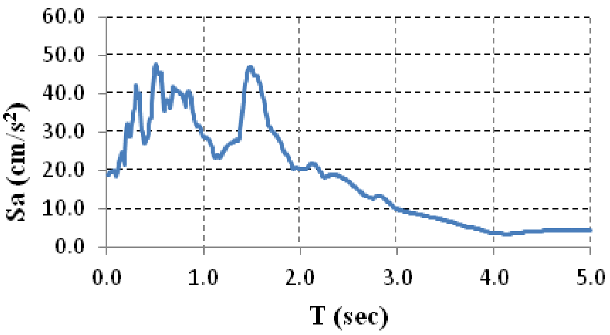

Figure 2. Pseudo-acceleration response spectrum with damping ratio equal to 0.05

For the linear analysis the seismic excitation used in this paper corresponds to the seismic design spectrum proposed by the CFE (1993). The spectrum corresponds to zone B and ground type I. Fig. 3 shows the spectrum.

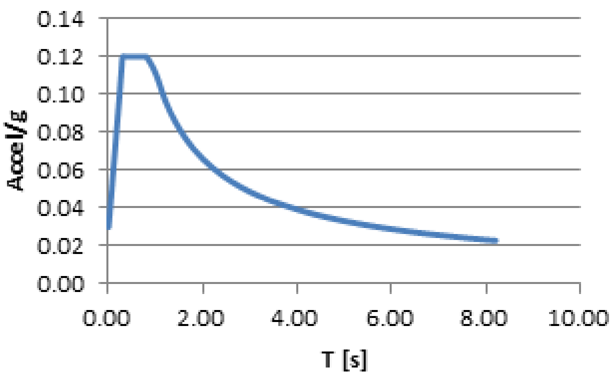

Figure 3. Acceleration design spectrum used for linear analysis

APPLICATION AND RESULTS

The Hospital located in Tlaxcala, Mexico, has several buildings. Here we only show the results associated with the buildings A and C. The structural system corresponds to a three-dimensional structure consisting of precast concrete frames. The columns have square section 0.60x0.60 m and are continuous over the entire height of the building; the supporting beams are of rectangular section of 0.90x0.55 m, the secondary girders have also rectangular section of 0.90x0.30 m. Floor systems are based on SPANCRETE^{TM} type prefabricated slabs (0.25 m thick). The joints between beams and columns were achieved using steel plates attached to the columns; these plates act as supports for the girders. The continuity in the nodes of the frame was established as a continuation in the steel bars of the beams through the same columns. In Fig. 4 the analytical model developed in SAP2000 software for the building C is shown. The dimensions, geometry and some mechanical properties were taken from architectural and structural plans.

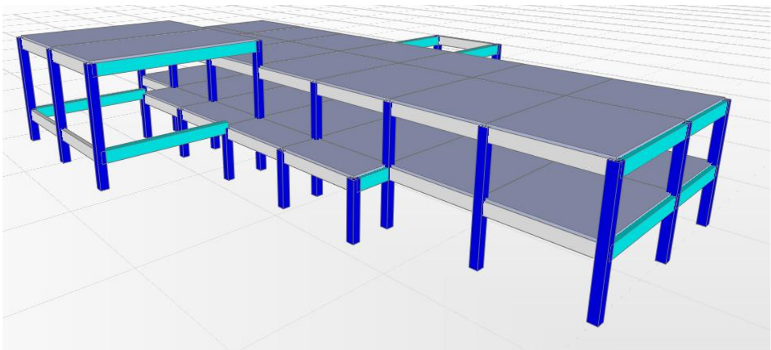

Figure 4. Structural model for the Hospital building developed in SAP2000 software

After applying the procedure described in previous sections we obtain the following results. Table 2 shows the vibration periods, for the buildings A, B and C, estimated empirically from experimental approach using ambient vibration records. We estimated the periods in the first three modes, transversal, longitudinal and rotational. In table 3 we present the vibration periods, for the buildings A an C, estimated analytically using the model developed in SAP2000 software. The values reported in Table 3 were reached after several iterations in the model because we modified some mechanical properties like the elasticity module of the materials.

Table 2. Vibration periods estimated from experimental procedure and using ambient vibration records

	BUILDING A		**BUILDING C**	
COMPONENT	**f[Hz]**	**T[s]**	**f[Hz]**	**T[s]**
Transversal	3.76	0.27	3.76	0.27
Longitudinal	3.94	0.25	3.94	0.25
Rotational	6.28	0.16	4.75	0.21

Table 3. Vibration periods estimated from analytical procedure using the SAP2000 model

	Building A	**Building C**
COMPONENT	T [s]	T [s]
Transversal	0.219	0.277
Longitudinal	0.152	0.259
Rotational	0.131	0.135

The safety factors were estimated from buildings A and C after applying Eq. (1). The values that were obtained from transversal and longitudinal directions of each building are show in Table 4. As we can see, the transversal directions present smaller values than the longitudinal direction, this phenomenon has been observed in other buildings studied by the authors (Ismael et al., 2012).

Table 4. Safety factor obtained from buildings A and C estimated from Eq. (1)

	Transversal direction		**Longitudinal direction**		**Transversal**	**Longitudinal**
Building	**Vb(y) [t]**	**V_{bR} [t]**	**Vb(y) [t]**	**V_{bR} [t]**	**Z(y)**	**Z(y)**
Building A	84.7	622.8	49.8	622.8	7.4	12.5
Building C	119.9	1411.7	47.0	1411.7	11.8	30.0

The School building studied in this paper is part of the infrastructure of UPAEP University; it corresponds to the high School located in the municipality of Cholula, Puebla. The geographical coordinates of the building are: 19.06 ° North Latitude and -98.29 ° West Longitude. Information about the structural details was available through structural plans that contain all drawings to characterize the overall structure, the properties of the materials, the dimensions of the cross sections of the structural elements and the assembly thereof. It is a three story building structured with rigid frames of reinforced concrete and diaphragm walls arranged in the transversal direction of the building. The building is irregular in both plan and elevation. The building has a total length of 47 m and its total height is 9.75 m, each interstory is 3.0 m high. The columns and beams have a rectangular cross section of 0.5x0.6 m and 0.3x0.5 m, respectively. In the longitudinal direction exists masonry walls covering three quarters of the height of the story, this can cause the presence of short columns, the problem of short column is part of another study. The floor is based on a one-way beam and slab system. Fig. 5 shows a view of the building.

Figure 5. Current view of the School building studied in this paper

In the Fig. 6 the 2-D mathematical model for non-linear analysis is presented. The model corresponds to the longitudinal frame and the dimensions are in meters. In order to simplify the analysis we assume that the torsional effects due to irregularity are small and a planar model keeps with good accuracy the behaviour of the building.

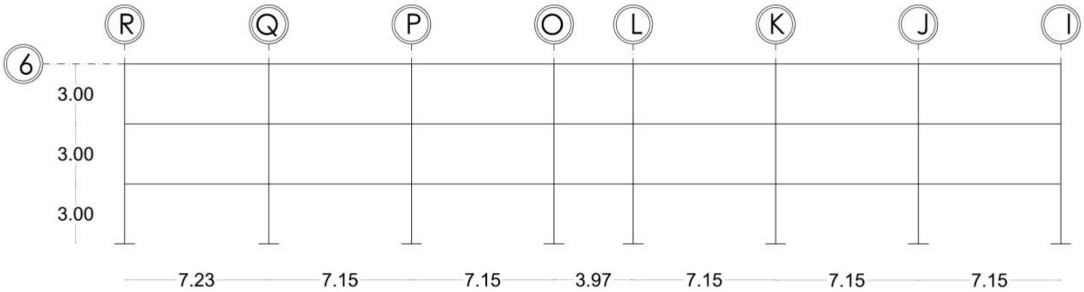

Figure 6. Mathematical model used for the non-linear analysis (step by step and pushover)

According with the previous sections, in the Fig. 7 we show the spectral ratios estimated for the building. The functions correspond to the spectral ratio in terms of frequency for each mode. In the Table 5 we show the estimated values of the frequency for each mode, these values correspond to the experimental and analytical modes, the former estimated using ambient vibration and the latter estimated using a mathematical model with calibrated properties see Ismael et al. (2012) for details.

Table 5. Experimental and analytical values of the modal frequencies on the School building

Mode	Experimental values		Analytical values
	f[Hz]	T [sec]	T [sec]
Longitudinal	4.98	0.20	0.22
Transversal	6.58	0.15	0.15
Rotational	7.22	0.14	0.14

The Fig. 8 represents pushover curve estimated according to the criteria given in corresponding section. From this curve we estimated the value of K_0 equals to 70.9 tons/cm and the deformation capacity u_F equals to 18.3 cm.

The seismic responses were obtained by applying the criteria given in the corresponding section. A sample of fifty structural models was simulated using the software SIESTRUEIH.EXE. For each model we use a scale factor in order to amplify the seismic excitation. The scale factor was also used for scaling the pseudo-acceleration response spectra. We computed the corresponding displacement response spectra using the known relationship between the two them. By doing this, we estimated the normalized seismic intensity that corresponds to $\eta = S_{dl}(T)/u_F$. $S_{dl}(T)$ is the ordinate of the linear displacement response spectrum corresponding to the fundamental period of the structural models and u_F is the deformation capacity defined before. The Fig. 9 shows an example of the seismic response computed from step by step analysis; the curve represents the relationship between the shear force at the base of the system (V_b) and the global lateral displacement (X_N). The above values were useful for estimating the values of K. Finally, for each structural model the Eq. (2) was employed to estimate the values of I_{SSR}.

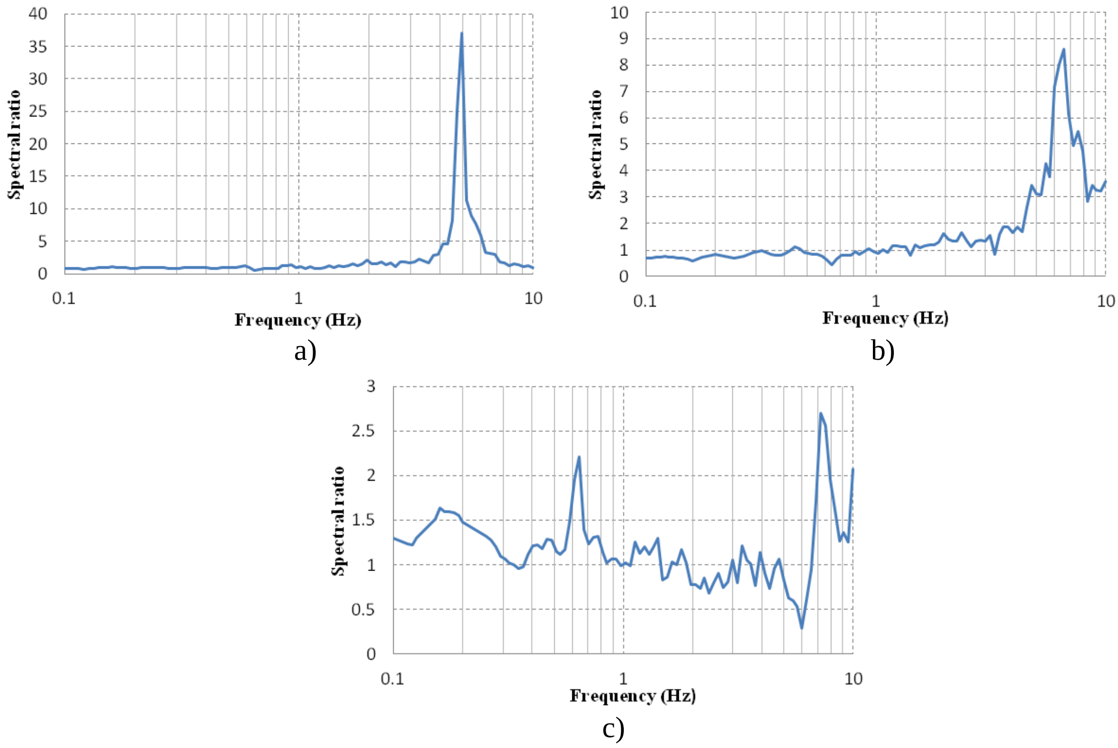

Figure 7. Spectral ratios estimated for the School building using ambient vibration; a) Longitudinal mode, b) Transversal mode, and c) Rotational mode

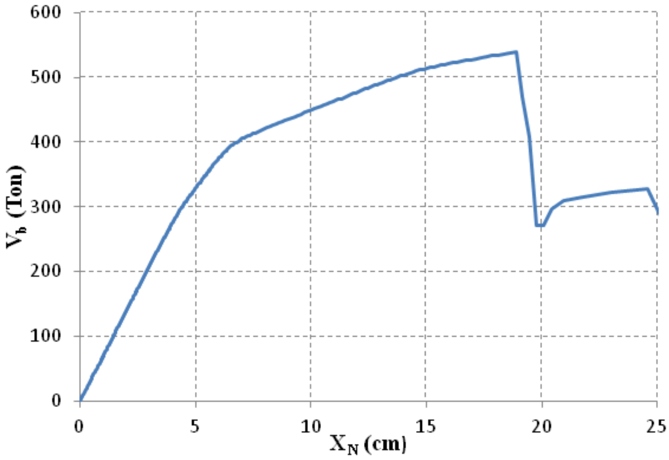

Figure 8. Pushover curve obtained from the School building (longitudinal direction)

The Fig. 10 shows the values of I_{SSR} in terms of the normalized intensity η. From the figure we can observe that for small levels of the normalized intensity (around 0.4) we can observe survival condition with small levels of damage (around 0.15). It is easy to see from the figure that the structural damage increases with the intensity. In order to estimate the collapse condition we need a normalized intensity around 0.8; this means that for the collapse condition of the building we need a linear displacement $S_{dL}(T)$=14.6 cm.

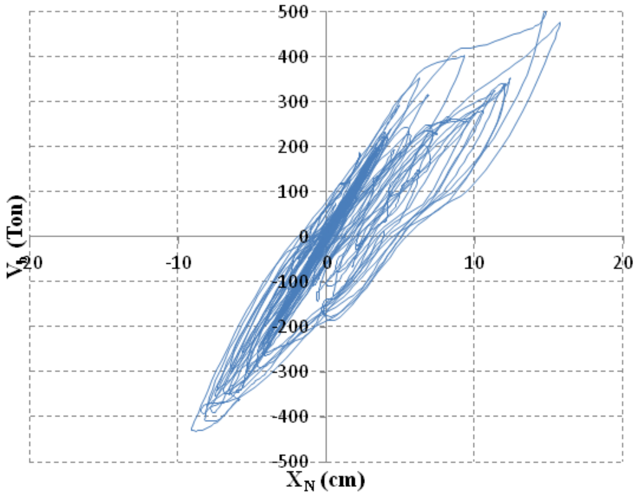

Figure 9. Example of the seismic response computed from the step by step analysis

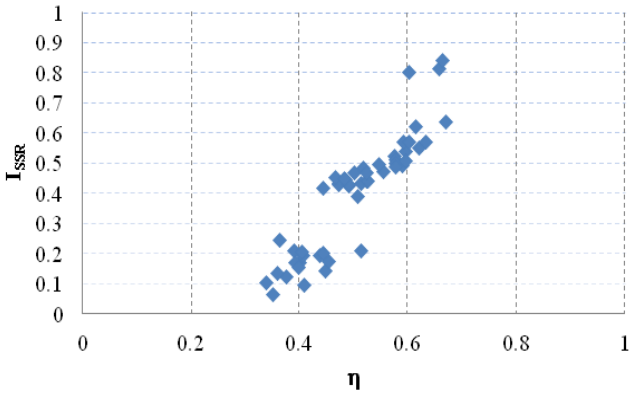

Figure 10. Values of I_{SSR} obtained from Eq. (2), in terms of normalized seismic intensity

CONCLUDING REMARKS

In this paper two procedures for estimating structural reliability of existing buildings were presented. The procedures takes into account the evaluation of some dynamic properties using ambient vibration records, these properties are useful to calibrate analytical models of the buildings. The simplified procedure can be employed for establishing a preliminary vulnerability level. The detailed procedure is more general and has a better accuracy because it employs a damage index that considers the reduction of secant stiffness of the structural system when this is subjected to an earthquake with given intensity; the non-linear responses are estimated for computing the damage index; the uncertainties related to the mechanical properties and the gravitational loads are considered. The procedures were applied to an existing building located in Central Mexico. The seismic excitation for the step by step analysis was obtained from the seismic local network of the UPAEP University and corresponds to an earthquake occurred in the Pacific coast of the Country. Estimations of non-linear response of the structural models were possible by using pushover analysis and step by step techniques. After analysing the results we can conclude that the building studied presents an acceptable level of reliability. Finally, the procedures presented here can be used to other kind of existing buildings and the information obtained can be useful for mitigating the seismic risk of existing buildings.

ACKNOWLEDGEMENT

The first author acknowledges the support of the Engineering and Research Departments of UPAEP for their support to develop this research. It also recognizes the active participation of the students of the School of Civil Engineering UPAEP for the support in the work of instrumentation of the School building, as special thanks to Antia Yaderi Lozano, Mauricio Barbosa, Alberto Ismael and Marcus Harper from Howard University.

REFERENCES

Cornell, C.A (1969). A probability-based structural code. *Journal of American Concrete Institute*, 66 (12).

CFE (1993). Manual de Diseño de Obras Civiles, Diseño por Sismo (Handbook of Civil Construction Design, Seismic Design, In Spanish), Electricity Federal Commission, Institute of Electrical Research, México.

Esteva, L., Díaz-López, O., García-Pérez, J. Sierra, G. and Ismael, E (2002). Simplified reference systems in the establishment of displacement-based seismic design criteria. *Proc. 12th European Conference on Earthquake Engineering*. London, England. Paper 419.

Esteva, L. and Ismael, E (2003). A maximum likelihood approach to system reliability with respect to seismic collapse. *Proc. 11th IFIP WG7.5 Working Conference*. Banff, Canada.

Esteva, L. and Díaz-López, O. (2006). Seismic reliability functions for complex systems based on a secant-stiffness reduction index. *Proc. 13th IFIP WG7.5 Working Conference*. Kobe, Japan.

Esteva, L., Díaz-López, O. and Ismael-Hernández, E. (2010). Seismic vulnerability functions of multi-storey buildings: estimation and applications. *Journal of Structure and Infrastructure Engineering*. Vol 6:1-2,3-16.

Ismael-Hernández, E., Alcazar-Pastrana, O., González-Gálaviz, M.A., Rodríguez-Zárate, R. and Ferrer-Toledo, H. (2012). Evaluación de la confiabilidad estructural de construcciones escolares (Structural reliability evaluation of school buildings, In Spanish). *Proceedings of the 18th National Conference on Structural Engineering*. Acapulco, Mexico.

Meli, R. (1976). Bases para los criterios de diseño estructural del proyecto del Reglamento de Construcciones para el Distrito Federal (Basis for earthquake resistant design criteria for the draft of Mexico City Building Code, In Spanish). Institute of Engineering, National University of Mexico. Report 375.

Mirza, S.A., and McGregor, J. (1979). Variation in dimensions of reinforced concrete members. *Journal of Structural Division*, ASCE. 105: ST4, 751-766.

Powel, G. H. (1973). DRAIN-2D user´s guide. Report No. EERC 73-22. Earthquake Engineering Research Center. California University, Berkeley.

Wang, M.L. and Shah, S.P. (1987). Reinforced concrete hysteresis model based on the damage concept. *Earthquake Engineering and Structural Dynamics*. 15, 993-1003.

Wathelet, M. (2005). Geopsy Poject. European project NERIES.