EVALUATION OF DEMAND AND CAPACITY FACTORS BASED ON RELIABILITY-BASED CRITERIA

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ABSTRACT :

The capacity and demand factors implicit in three reinforced concrete 5-, 10- and 15-story buildings designed in accordance with the Mexico City Design Regulations 2004 are calculated. In order to reach this objective it was followed a procedure similar to that proposed by Cornell and collaborators. The evaluation is performed for three structural limit states: serviceability, life safety and near-collapse.

KEYWORDS: Capacity and demand factors, aleatory and epistemic uncertainties, structural reliability

1. INTRODUCTION

Modern guidelines for seismic design and structural seismic evaluation of buildings present a new approach that use the Demand and Capacity Factor Design (DCFD) format instead of the traditional Load and Resistance Factors Design (LRFD) format. The main difference between these two formats (DCFD and LRFD) is that the first considers in an explicit way the aleatory and the uncertainty of the structural demand and of the seismic excitation, associated with different limit states.

In the future it may be convenient to adopt the DCFD format, so it will be necessary to evaluate the demand and capacity factors that are implicit in buildings designed in accordance with a (reliable) seismic code.

In the present study, the demand and capacity factors that are implicit in three reinforced concrete buildings are calculated. Each evaluation corresponds to three limit states: *1) Serviceability*, which is associated with a performance level in which the yielding drift value for the peak story drift is presented. *2) Life safety.* The limit state is adopted here such that the median value of the maximum capacity for the peak story drift is equal to 0.02. *3) Near-collapse*, which is associated with the peak story drift that is capable of resisting the structure, just before it becomes unstable.

2. PROCEDURE FOR EVALUATING THE RESISTANCE FACTOR (ϕ) AND THE LOAD FACTOR (γ) THAT ARE IMPLICIT IN THE BUILDINGS ANALYZED

The following describe the procedure (Cornell et al 2002) to calculate the resistance (ϕ) and load (γ) factors implicit in structural designs made in accordance with the Mexico City Design Code (RCDF-2004).

1. First, the ground motions that will affect the structures are selected. In our case, fourteen ground motions were chosen. These motions were recorded on soft soil in Mexico City.
2. We study the buildings (in our case reinforced concrete structures), and the structural demand was calculated for the fourteen ground motions scaled to different intensity levels. Based on the results, the median value of the demand ($\hat{D}$) was estimated for the serviceability, the life safety and the near-collapse limit states.
3. Next, the total uncertainties (i.e., aleatory σ_R and epistemic σ_U) associated with the structural

demand, for the limit states under evaluation, were obtained.

4. The median capacity ($\hat{C}$) was obtained for the three limit states. The median structural capacity is estimated by means of incremental dynamic analyses (‘step by step’ analyses in time). This capacity is measured as the peak story drift.
5. Next, the total uncertainties (i.e., aleatory σ_R and epistemic σ_U) associated with the capacity of the buildings under consideration, are estimated.
6. The *r* parameter (that represents the slope of the seismic hazard curve for a given intensity), is obtained.
7. The capacity factor value for each building is estimated as follows (Jalayer and Cornell, 2002): $\phi = \exp\left[-\frac{1}{2}\frac{r}{b}\sigma_{CT}^2\right]$, where the *r* and *b* variables depend of the seismic hazard of the site where the structures are located and of the structural demand, respectively, and σ_{CT}^2 is the variance of the structural capacity (C). The subscript T represents the total variance that includes both aleatory σ_R and epistemic σ_U uncertainties.
8. The demand factor value is estimated as follows: $\gamma = \exp\left[\frac{1}{2}\frac{r}{b}\sigma_{DT}^2\right]$, where σ_{DT}^2 is the variance in the structural demand (D). The subscript T represents the total variance which includes both aleatory and epistemic uncertainties associated with the structural demand.

The previous procedure was applied for the analysis of three reinforced concrete buildings (5-, 10- and 15-story, three-bay buildings) located on soft soil in Mexico City.

In what follows a series of tables are obtained. These tables contain different parameters such as: *b* and *r*, aleatory σ_R and epistemic σ_U uncertainty values, median demand $\hat{D}$ and median capacity $\hat{C}$ values, and finally, the capacity ϕ and demand γ factors for each building, associated with three limit states.

3. CHARACTERISTICS OF THE STRUCTURES AND OF THE GROUND MOTIONS

3.1 Structures Analyzed

The following describes the main features of the three reinforced concrete office buildings analyzed.

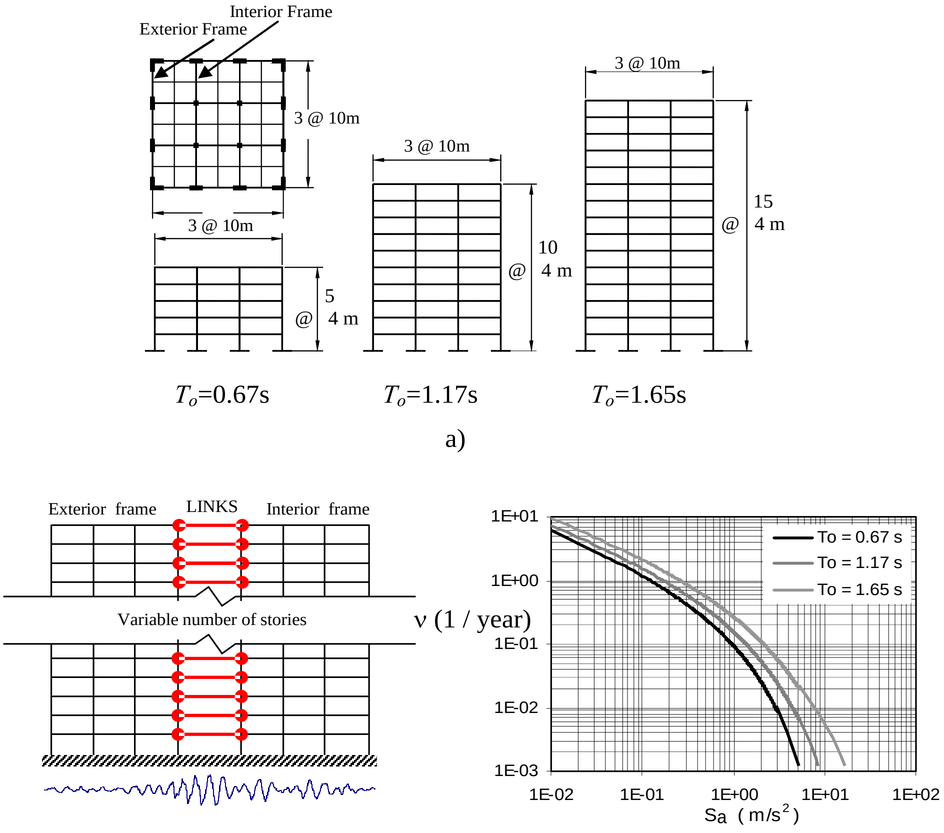
The buildings were designed in accordance with the latest version of Mexico City Design Regulations (RCDF-2004) by three well recognized Mexican engineering firms. The geometric properties of the structures are shown in Figure 1a. The mean values of the fundamental periods of vibration (T_0) of the 5-, 10- and 15-story structural frames are equal to 0.67, 1.17 and 1.65s, respectively, and their yield strength coefficients (Cs) are 0.34, 0.4 and 0.17, respectively (Montiel 2006).

Each building contains exterior and interior structural frames. The dynamic interaction between these was taken into account by means of two-dimensional structural models in which the exterior and the interior frames are connected by hinged links (see Figure 1b). The frames were constituted by flexural beams and columns. The moment–rotation ratios for each element were calculated assuming the model for confined concrete originally proposed by Kent and Park, 1991 and modified by Park et al, 1982. The axial stress–strain ratios corresponding to the steel bars were represented by means of Mander model, (Mander 1984). The hysteretic structural behavior was assumed bilinear with the ratio of the post-yielding to the initial stiffness equal to 3.0%.

3.2. Ground Motions and Seismic Hazard Curves

The structures were subjected to ground motions recorded at the Ministry of Communications and Transportation station (SCT), located on soft soil in Mexico City. The corresponding seismic hazard curves (associated with T_0 = 0.67s, 1.17s and 1.65s) at the SCT site are shown in Figure 1c (Alamilla, 2004). The ground motion spectra have dominant periods between 1.5 and 2.2s, and correspond to subduction events with magnitude M > 5.6. The response spectra corresponding to five percent of critical damping are shown in Figure 2a, which presents a logarithmic vertical axis. The figure gives an idea about the scaling factors used in the analyses.

Figure 2b shows the response spectra of the motions scaled to the same spectral acceleration level (Shome and Cornell, 1999). In this case, it corresponds to a return period T_R = 50 years (Figure 1c). Figure 2b also shows with a thick black line the arithmetic mean values of the fourteen scaled spectra.



a)

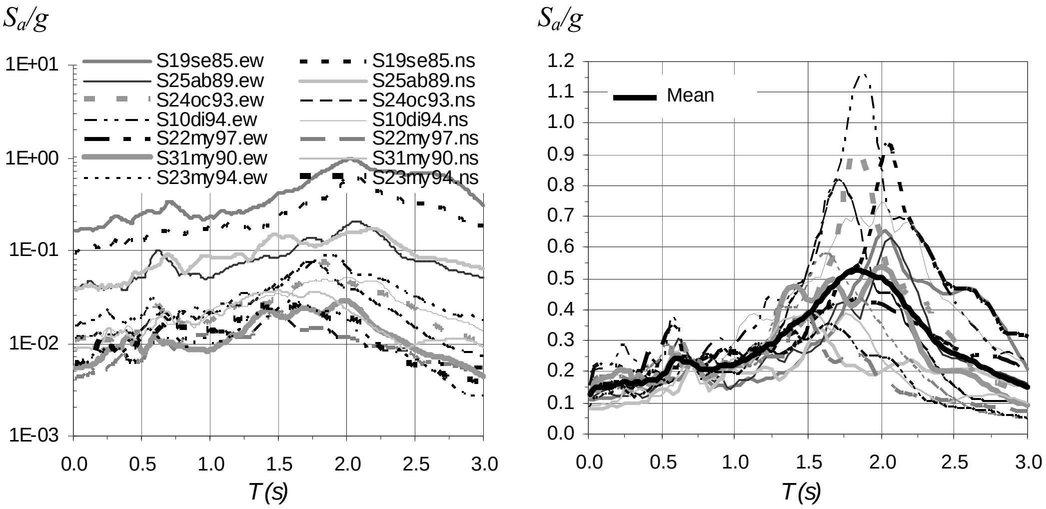
b)

c)

Figure 1. a) Plan and elevation of the buildings. b) Two-dimensional structural model. c) Seismic hazard curves for the SCT site.

4. CALCULATING THE MEDIAN DEMAND OF THE PEAK STORY DRIFT ($\hat{D}^{\nu_0}$) ASSOCIATED WITH EACH LIMIT STATE

In this section we obtained the median values of the structural demand ($\hat{D}$) of the buildings subjected to ground motions scaled at different intensity levels $\left(S_a/g\right)$. These values are obtained from non-linear dynamic analyses for the fourteen ground motions selected and scaled to the seismic hazard associated with the serviceability, life safety and near-collapse limit states. Table 1 presents the median value of the structural demand associated with each limit state ($\hat{D}^{V_0}$).



a) Without scaling b) T_o = 0.67s

Figure 2. Pseudo-acceleration spectra of the ground motions. ξ = 5 %, T_R = 50 years.

Table 1. Median of the peak story drift ($\hat{D}^{V_0}$) corresponding to the three buildings

Frame	**Serviceability limit state** $\hat{D}_y$	**Life safety limit state** $\hat{D}_{life}$	**Near-collapse limit state** $\hat{D}_{col}$
5-story	0.003	0.012	0.017
10-story	0.007	0.016	0.024
15-story	0.005	0.0168	0.019
AVERAGE	**0.005**	**0.015**	**0.02**

4.1 Aleatory Uncertainties (σ_{DR}) *associated with the Structural Demand*

Table 2 presents the aleatory uncertainties (σ_{DR}) associated with the structural demand.

Table 2. Aleatory uncertainties (σ_{DR}) **associated with the structural demand**

Frame	**Serviceability limit state** $\sigma_{DR\,y}$	**Life safety limit state** $\sigma_{DR\,life}$	**Near-collapse limit state** $\sigma_{DR\,col}$
5-story	0.263	0.757	1.296
10-story	0.097	0.411	0.891
15-story	0.073	0.390	0.629
AVERAGE	**0.14**	**0.52**	**0.94**

4.2 Epistemic Uncertainties (σ_{DU}) *associated with the Structural Demand*

Table 3 presents the epistemic uncertainties (σ_{DU}) associated with the structural demand. Epistemic uncertainties are proposed in the opinion of the authors. The highest values are those corresponding to the 15-story building and to the life safety and near-collapse limit states.

Table 3. Epistemic uncertainties (σ_{UD}) **associated with the structural demand**

Frame	**Serviceability limit state** $\sigma_{DU\,y}$	**Life safety limit state** $\sigma_{DU\,life}$	**Near-collapse limit state** $\sigma_{DU\,col}$
5-story	0.15	0.30	0.30
10-story	0.20	0.35	0.35
15-story	0.25	0.40	0.40
AVERAGE	**0.20**	**0.35**	**0.35**

5. CALCULATION OF THE STRUCTURAL CAPACITY OF THE BUILDINGS

In order to calculate the capacity factor (ϕ) of the buildings, we performed Incremental Dynamic Analyses (IDAs, Vamvatsikos and Cornell, 2002) using the fourteen seismic records mentioned above.

5.1 Calculating the Median Capacity of the Peak Story Drift ($\hat{C}$)

Based on the IDAs curves, the median structural capacity ($\hat{C}$) associated with each limit state is obtained. These values are shown in Table 4. The values were obtained for the serviceability limit state ($\hat{C}_y$) which is associated with the yielding story drift of the structure. The yielding story drift is obtained from a (bi-linear) fit to the IDA's curves. The median capacity for the life safety limit state ($\hat{C}_{life}$) is associated with the median capacity value of the peak story drift equal to 0.02. The capacity corresponding to the near-collapse limit state ($\hat{C}_{col}$) is associated with the peak story drift level that is capable of resisting the structure before it becomes unstable.

Table 4. Median capacity $(\hat{C})$ **of the peak story drift for the three buildings and different limit states**

Frame	**Serviceability limit state** $\hat{C}_y$	**Life safety limit state** $\hat{C}_{life}$	**Near-collapse limit state** $\hat{C}_{col}$
5-story	0.0037	0.02	0.045
10-story	0.0072	0.02	0.040
15-story	0.0045	0.02	0.052
AVERAGE	**0.0051**	**0.02**	**0.046**

5.2 *Aleatory Uncertainties* (σ_{CR}) *associated with the Structural Capacity* $(\hat{C})$

Table 5 presents the aleatory uncertainties associated with the structural capacity of the buildings.

Table 5. Aleatory uncertainties (σ_{CR}) **associated with the structural capacity**

Frame	**Serviceability limit state** $\sigma_{CR\,y}$	**Life safety limit state** $\sigma_{CR\,life}$	**Near-collapse limit state** $\sigma_{CR\,col}$
5-story	0.051	0.10	0.18
10-story	0.034	0.12	0.26
15-story	0.065	0.14	0.29
AVERAGE	**0.05**	**0.12**	**0.24**

5.3 *Epistemic Uncertainties* (σ_{CU}) *associated with the Structural Capacity*

Table 6 shows the epistemic uncertainties associated with the structural capacity of the buildings. The values are proposed in the opinion of the authors. The highest values are proposed for the 15-story building and for the life safety and near-collapse limit states.

Table 6. Epistemic uncertainties (σ_{CU}) **associated with the structural capacity**

Frame	**Serviceability limit state** $\sigma_{CU\,y}$	**Life safety limit state** $\sigma_{CU\,life}$	**Near-collapse limit state** $\sigma_{CU\,col}$
5-story	0.15	0.30	0.30
10-story	0.20	0.35	0.35
15-story	0.25	0.40	0.40
AVERAGE	**0.20**	**0.35**	**0.35**

6. CALCULATION OF THE CAPACITY FACTOR (ϕ) AND THE DEMAND FACTOR (γ)

In order to calculate the *capacity* (ϕ) and the *demand* (γ) *factors* it was necessary to obtain the parameter b associated with the demand (for the limit state under consideration), as well as the parameter r that represents the slope of the seismic hazard curve corresponding to the intensity level of interest.

The parameter b was obtained from the $\hat{D}$ versus S_a/g curve, and the parameter r from the seismic hazard curve associated with the fundamental period of the structure (Montiel and Ruiz 2007).

The b and r values for each limit state are presented in Tables 7 and 8, respectively. Note that the largest values correspond to life safety and near-collapse limit states.

With the aleatory and epistemic uncertainties associated with the capacity σ_{CT}^2 and with the demand σ_{DT}^2, and with the b and r parameters, the capacity factor (ϕ) and the demand factor (γ) are estimated by means of the equations 6.1 and 6.2:

$$\phi = \exp\left[-\frac{1}{2}\frac{r}{b}\sigma_{CT}^{2}\right] < 1 \tag{6.1}$$

$$\gamma = \exp\left[\frac{1}{2}\frac{r}{b}\sigma_{DT}^{2}\right] > 1 \tag{6.2}$$

The ϕ and γ values are shown in Tables 9 and 10.

Table 7. Parameter *b* corresponding to the three buildings and different limit states

Frame	**Serviceability limit state** b_y	**Life safety limit state** b_{life}	**Near-collapse limit state** b_{col}
5-story	1.255	4.35	4.35
10-story	1.120	2.60	2.60
15-story	0.650	1.10	1.10
AVERAGE	**1.008**	**2.683**	**2.683**

Table 8. Slope of the seismic hazard curve *(r)* for the three buildings and different limit states (SCT site)

Frame	**Serviceability limit state** r_y	**Life safety limit state** r_{life}	**Near-collapse limit state** r_{col}
5-story	2.76	3.80	3.80
10-story	2.20	2.70	2.70
15-story	1.45	2.50	2.50
AVERAGE	**2.14**	**3.00**	**3.00**

Table 9. Capacity factor (ϕ) for the three buildings and different limit states

Frame	**Serviceability limit state** ϕ_y	**Life safety limit state** ϕ_{life}	**Near-collapse limit state** ϕ_{col}
5-story	0.97	0.96	0.95
10-story	0.96	0.85	0.80
15-story	0.93	0.82	0.76
AVERAGE	**0.95**	**0.88**	**0.84**

Table 10. Demand factor (γ) for the three buildings and different limit states

Frame	Serviceability limit state γ_y	Life safety limit state γ_{life}	Near-collapse limit state γ_{col}
5-story	1.04	1.34	1.5
10-story	1.05	1.35	1.7
15-story	1.08	1.43	1.88
AVERAGE	**1.06**	**1.37**	**1.69**

7. CONCLUSIONS

The capacity and demand factors implicit in three reinforced concrete 5-, 10- and 15-story buildings were calculated. The structures were design in accordance with the Mexico City Seismic Code (RCDF-2004). The buildings have a fundamental period less than the dominant period of the soil (T_s = 2s).

The average capacity factors were 0.95, 0.88 and 0.84, and the average demand factors were 1.10, 1.40 and 1.70 for the three limit states: serviceability, life safety and near-collapse, respectively. The lower capacity factor and the higher demand factor correspond to the near-collapse limit state.

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