

INELASTIC SEISMIC BEHAVIOR COMPARATION OF A TYPICAL REINFORCED CONCRETE 10 LEVEL BUILDING WITH FRAMES AND SHEAR WALLS DESIGNED WITH TWO CODES

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SUMMARY

The seismic elastic and inelastic behavior of a typical reinforced concrete 10 levels building in Mexico city designed according to the RDF-1993 and RDF-2003 (to be approved) Codes is compared. It is intended to corroborate that the modifications made to the RDF-1993 Code provide safe structures with suitable behavior facing severe earthquakes, according to the type and importance of the structure and kind of soil where will be build, based on the new seismic zone of the Valley of Mexico; the previous analysis is made based on the RDF-1993, current nowadays. The building is structured with longitudinal direction frames and with shear wall frames in the transversal direction. The design is made with the modal dynamics seismic analysis and the seismic spectra corresponding to zone III (soft) of the RDF-1993 Code and zone IIIb (soft) of the RDF-2003 Code; the dimensions of the structural elements are determined satisfying the permissible relations of the relative lateral displacements between the story height (0.012 in longitudinal direction and 0.006 in transversal direction); to satisfy the limit state of failure, a seismic behavior factor Q= 3 is used, designing with the general requirements and with the special requirements needed for ductility. The use is for offices (B group); the designs are made considering the gravitational loads and the second order effects. The calculation of the inelastic responses is done with dynamic step by step analysis with the SCT-EW-1985 register, earthquake representative of the structural damages on the soft zone in Mexico city; the local and global ductility demands are determined, the possible tendencies of failure mechanisms and no-lineal deformations in the structural elements. The inelastic responses, after being satisfied the RDF-2003 design conditions, show satisfactory structural behavior; the majority of the beams have less plastic hinges.

INTRODUCTION

Mexico City suffers the seismic effects because it is mostly located on high compressible soil that originates the amplification of waves seismic which arrive from the pacific coast, producing seismic motions of higher intensity Mexico City construction design is ruled by the Federal District Construction

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Code and its Complementary Technique Norms (NTC), current from 1993 (RDF-93)[1]. A new version of the Code and its NTC is now accomplished, missing only its publication in an official way; a new ubication zone of the soil in the soft zone is proposed, subdividing the previous zone III on the III_a, III_b, III_c and III_d ones. It is attended that the new edition is being approved this year (RDF-03)[2]. The seismic elastic and inelastic behavior of a 10 level reinforced concrete building with foundation box and friction piles is compared, designed according to the RDF-93 and RDF-03 Codes and its respectively NTC. The horizontal relative displacements between the story height are limited in order not to exceed the permissible limit $\gamma_p \leq 0.012$ in the longitudinal direction and $\gamma_p \leq 0.006$ in the transversal direction; the limit failure state is checked considering a seismic behavior factor Q= 3, so that it is necessary to design with the ductile frame requirements, beside of the general requirements. The design is made with a modal three-dimensional dynamic seismic analysis with the corresponding seismic spectra of zone III (soft soil) of the RDF-93 and zone III_b (soft soil) of the RDF-03.

The calculation of the reinforcement steel of the different structural elements is made taking in to consideration all the possible combinations of gravitational and seismic loads, including the second order effects. The seismic bidirectional effects are included checking the two horizontal components acting simultaneously with the 100 % in one direction and the 30 % in the orthogonal direction; the vertical component is not considered important. Comparisons, with both Codes, of the structural elements of the transversal sections dimensions, the vibration periods, the maxima lateral displacements, the design mechanical elements (internal actions) and the reinforcement steel are made. For the calculations of the inelastic responses, dynamic analysis step by step with the acceleration register SCT-EW obtained during the earthquake of September 19th 1985, representative of the compressible zone in Mexico City are made; the local and global ductility demands, the possible failure mechanisms and the non-linear deformations in structural elements are determined.

CRITERIA OF ANALYSIS AND DESIGN

The structure must be kept inside the service limit state in front of earthquakes of moderate intensity though non structural minor damages are permitted; in front of considerable intensity earthquakes it could present important structural damages, but not to get to the structure collapse. In the seismic design it is very important to know the structural elements inelastic response in order to determine the adequate combination of resistance, stiffness and ductility (capacity for energy dissipation); a framed structure with strong columns and weak beams is recommended, so that when entering the inelastic range the plastic hinges are presented at the beam extremes and the column plasticity is avoided, because if a column fails in a determined story, there is a risk that may cause the collapse of all the columns of the same story and then the failure of all the building.

DESCRIPTION OF THE STRUCTURE

This is a typical Mexico City reinforced concrete 10 level building from the street level, plus the 2 level foundation stiff box with a basement and the beam grid, supported on point piles. This is a B group structure (offices), except the basement level which is the parking. The structure is located on soft soil: zone III, RFD-93 and zone III_b, RDF-03. It is rectangular type plant with 36x18 m dimensions, with four 9 meters spaces and three 6 meters spaces in X and Y directions respectively; it is structured with X direction (longitudinal) frames; in Y direction (transversal), the internal axes are frames and the two external axes have reinforcement concrete walls. Figures 1 to 3 show the principal structural characteristics of the building. The columns are rectangular, oriented with their bigger dimension in X direction, of same sizes from ground level to N2 level, from N2 level to N6 level, and from N6 level to N10 level. In X direction there are secondary beams at the middle of each slab panel. The dimensions of

the principal beams, both directions, and the secondary ones do not change in all the height. The slab thickness in all levels is of 10 centimeters. The foundation box walls have 50 centimeters thickness; the foundation slab has 40 centimeters thickness; the foundation beams have 50 centimeters wide in X direction, and 40 centimeters in Y direction. The concrete is class 1 with a resistance compression $f'_c = 250 \text{ kg/cm}^2$, a volumetric weight in fresh state of 2400 kg/m³ and a modulus of elasticity $E_c = 14000 \sqrt{f'_c}$. The reinforcement steel has a fluency stress $f_y = 4200 \text{ kg/cm}^2$.





MEASUREMENTS IN METERS

Figure 2. Cross section throughout longitudinal axes (X direction)



Figure 3. Cross section throughout axes C and A (Y direction)

LEVEL	RDF-93	RDF-03	
N6 to N10	60x60	60x60	
N2 to N6	75x60	80x60	
BASEMENT to N2	95x60	100x60	

Table 1. Cross-sectional column dimensions (centimeters)

Table 2. Cross-sectional beam dimensions (centimeters)

BEAMS	RDF-93	RDF-03	
PRINCIPALS (X)	75x40	80x40	
PRINCIPALS (Y)	65x35	65x35	
SECONDARY	65x35	65x35	

LEVEL	RDF-93	RDF-03	
N6 to N10	15	15	
N2 to N6	25	25	
BASEMENT to N2	30	30	

 Table 3. Thickness wall dimensions (centimeters)

STRUCTURAL DESIGN RESPONSES CALCULATION

Vibration periods

Table 4 shows the period values of the three first vibration modes in the three main directions of each analysis case: RDF-93 and RDF-03.

	RDF-93	RDF-03	RDF-93	RDF-03	RDF-93	RDF-03
PERIOD (S)	Х	Х	Y	Y	Torsion	Torsion
T ₁	1.489	1.365	0.923	0.917	0.669	0.658
T ₂	0.502	0.466	0.226	0.226	0.161	0.160
T ₃	0.285	0.264	0.104	0.104	0.074	0.074

 Table 4. Vibration periods (seconds)

The periods are bigger in X direction, which indicates that the structure is more flexible in such direction; in Y direction, the exterior axes walls give a great lateral stiffness. The periods are lightness smaller in the case of RDF-03 design, according to the observed in dimensions. Figure 4 shows the location of the fundamental periods of vibration of the building in both directions regarding the elastic and inelastic response spectra of the SCT-EW-85 register; it is to be expected a bigger response in X direction.



Figure 4. Location of the fundamental periods of vibration, both directions, in the elastic and inelastic response spectra of the SCT-EW-85 register

Maximum horizontal displacements

Figure 5 has the responses of the modal spectra dynamic analysis, earthquake in X and Y directions, both Codes. In X direction the structure behaves as a shear beam in order to the main work in frames, and in the Y direction a behavior patron flexure beam type, due to the important shear walls participation in A and E exterior axes; the lateral displacements are smaller in the transversal building direction.



Figure 5. Maximum horizontal displacements, earthquake in X and Y directions

Relative lateral displacement between the story height ratios (drifts)

The maximum drifts, RDF-93 and RDF-03 designs, earthquake in X and Y directions, is closed to the permissible limit; the transversal direction is more stiff, but acceptable because it is impossible to reduce in a excessive way the structural elements dimensions, due to the necessary geometric requirements demands for ductile frames (see Figure 6).



Figure 6. Relative lateral displacement between the story height, earthquake in X and Y directions

Mechanical design elements

With the most critical loads combination results, in beams it is of great interest the last bending moments, positives and negatives, in both extremes as well a the last shear force; but regarding columns and walls the last bending moments in mayor and minor directions besides the last axial force of the most critic combination, and the last shear forces of both directions are important. The calculation of the reinforcement steel of each structural element is made according to the NTC-Concrete RDF-93 and RDF-03 requirements, checking the special ductile frames conditions.

INELASTIC SEISMIC RESPONSES CALCULATION

The time history with the interest structure in both directions is checked considering A, C and 2 axes; such axes were previously designed with the RDF-93 and RDF-03 norms; dynamic inelastic analysis are made with the SCT accelerogram, E-W component, registered in September 19th 1985 (Figure 7).



Figure 7. SCT- EW acceleration register, earthquake of September 19th 1985

Maximum horizontal displacements and global ductility demands

Figures 8 to 10 compare the envelopes of the elastic and inelastic horizontal displacements of 2, C and A axes, respectively, both Codes. The maximum lateral displacements in the long building direction (2 axe) are bigger than the ones in short direction (A and C axes), because of the concrete walls influence in the lateral stiffness of the structure in transversal direction. The inelastic analysis displacements of short axes (A and C axes) present a little inelastic demand; the elastic and inelastic displacements of the long axe (2 axe) have between them because many of their structural elements present considerable inelastic deformations. The deformation behavior pattern of A and C axes (transversal direction) corresponds to a cantilever beam, due to the important concrete walls participation in the lateral stiffness; in the longitudinal building direction. With the RDF-03 resistances the responses are practically the same as the RDF-93 ones; they might have more important differences for axe 2, due to the bigger non-lineal deformations in this axe.



Figure 8. Maximum horizontal displacements comparison, axe 2



Figure 9. Maximum horizontal displacements comparison, axe C



Figure 10. Maximum horizontal displacements comparison, axe A

Table 5 compares the maximum global ductility demands, μ_G , of 2, C and A axes, both Codes designs; the demands are calculated as the ratio of the roof maximum lateral displacement during the inelastic behavior between the roof lateral displacement at the moment the first plastic hinge is presented.

AXE	Δ fluency lateral (cm)		Δ maximum inelastic (cm)		μ_G maximum	
	RDF-93	RDF-03	RDF-93	RDF-03	RDF-93	RDF-03
2	12.05	10.48	31.86	16.86	2.64	1.69
С	4.34	4.15	5.91	6.02	1.36	1.45
А	4.62	5.06	16.70	22.25	3.61	4.40

Table 5. Maximum global ductility demands of 2, C and A axes, RDF-93 and RDF-03 designs

Relative lateral displacement between the story height ratios (drifts)

Figures 11 to 13 compare the structural 2, C and A axes drifts, both Codes, with similar differences to the previous response observation. Based on the drifts, what type of damages should be expected in the structural and non-structural elements studied building can be defined, comparing against the permissible levels of 0.006 for the short direction and 0.012 for the long building direction. The behavior pattern of this kind of response varies according to the analyzed direction; for the direction in which the frames work predominates (longitudinal direction) the maximum responses tend to concentrate in the lower stories; and when the walls work (transversal direction) dominates, the responses tend to increase o to have similar amplitudes in upper stories.



Figure 11. Relative lateral displacement between story height ratio comparisons, axe 2



Figure 12. Relative lateral displacement between story height ratio comparisons, axe C



Figure 13. Relative lateral displacement between story height ratio comparisons, axe A

Basal shear force-lateral roof displacement ratios

Figures 14 and 15 present the elastic and inelastic axis 2 results with RDF-93 and RDF-03, respectively; comparing elastic and inelastic cases, bigger variations are presented with the RDF-93 design. The interior axis (C axis) of the short direction does not practically present an inelastic behavior. A axis (figures 16 and 17) shows a lateral stiffness lightly bigger with the RDF-03 design; there are important variations between the elastic and inelastic results, which indicates the presence of deformations in the non-linear range, with a most severe work in the plastic range than in the interior axes.



Figure 14. Basal shear force-lateral roof displacement ratios, 2 axis, RDF-93 design



Figure 15. Basal shear force-lateral roof displacement ratios, 2 axis, RDF-03 design



Figure 16. Basal shear force-lateral roof displacement ratios, A axis, RDF-93 design



Figure 17. Basal shear force-lateral roof displacement ratios, A axis, RDF-03 design

Global distribution of the plastic hinges and maximum demands local ductility developed in beams, columns and walls

Figures 18 to 20 show global distribution of plastic hinges in 2, C and A axes respectively, resistances with RDF-93 and RDF-03. It is corroborated that 2 and A axes present more inelastic behavior; in C axis only some 1 and 2 level beams reach their flexure fluency. Generally, apart from the structural axis, the tendency of the failure mechanics is a beam type; this means that the strong column-weak beam design philosophy is accomplished, after satisfying the NTC ductile frames requirements of RDF-93 and RDF-03; with this kind of local level damage a bigger energy dissipation that is introduced by the earthquake to the interested structure is obtained, and therefore a bigger global ductility. 2 axis, RDF-93 design, presents plastic hinges in the majority of the beams extremes, except a few of the upper levels and extreme clears; with the RDF-03 design the majority of the beams present plastic hinges in their extremes, but in the superior levels are only present in the side frame clears. For both Codes the PB-N1 story column inferior extremes have inelastic deformations. Comparing the RDF-93 and RDF-03 designs of C axis, the plastic hinges distribution is similar in both cases; it is concentrated in the beams extremes of the two lower levels, none in the columns. In A axis, a similar behavior is presented, independently from the Code type; this means that all the beams articulate in its extremes and the lower extremes of the two shear walls from the first story.

Figures 21 to 25 show the maximum local ductility demands developed in beams, columns and walls in 2, C and A axes, with the RDF-93 and RDF-03 resistances. It is corroborated that the structural members of 2 axis present a bigger inelastic behavior; in C axis the inelastic deformations are very small; the coupling beams of A axis tend to fluency in a similar form regarding the height, perhaps a little bigger in the first level; all the beams in this axis present plastic hinges due the enormous lateral walls stiffness regarding the beams that pretend to couple the two walls work, which tend to work each one of them in a independent way. All the beams, including 2 and A axes, have congruent and manageable maximum ductility demands from the point of view of the practical design. Beams of 2 axis (figure 22) present a great variation of the local ductility developed demands among the designs with the RDF-93 and RDF-03. Beams from C axis (figure 22) show small ductility demands, similar with both Codes. Beams of A axis (figure 23) have responses lightly bigger for the RDF-03 design case.







Figure 19. Global distribution of plastic hinges, C axis, RDF-93 and RDF-03 designs

In the case of columns and walls only have plastic hinges in the PB-N1 inferior story extreme, congruent with the beam mechanism tendency which is observed in each structural studied axis; the maximum local ductility demands are rather small; in C axis there is no fluency in columns.



Figure 20. Global distribution of plastic hinges, A axis, RDF-93 and RDF-03 designs



Figure 21. Maximum local ductility demands developed in beams, 2 axis, RDF-93 and RDF-03 designs



Figure 22. Maximum local ductility demands developed in beams, C axis, RDF-93 and RDF-03 designs



Figure 23. Maximum local ductility demands developed in beams, A axis, RDF-93 and RDF-03 designs



Figure 24. Maximum local ductility demands developed in columns, 2 axis, RDF-93 and RDF-03 designs



Figure 25. Maximum local ductility demands developed in walls, A axis, RDF-93 and RDF-03 designs

CONCLUSIONS

The structural elements dimensions are lightly bigger with the RDF-03 design; these differences are of scarcely 5 % in inferior level columns and of 6 % in principal beams of the structure longitudinal direction; the principal and secondary beams in the transversal direction are the same in both Codes; the walls conserve the same thickness with both Codes; this is, the designed building with RDF-03 results with a scarcely bigger lateral stiffness. The drifts show important differences between the long and short directions; the maximum values in longitudinal direction are of 0.0113 and 0.0105 for the RDF-93 and RDF-03, respectively, against the permissible value of 0.012; in short direction the maxima are 0.0046 and 0.0051, and the permissible limit is 0.006.

As a result of the step by step inelastic analysis, with both Codes design, the failure mechanisms tendency that is presented is the one of strong column-weak beam, that permits to reach bigger ductility and bigger seismic energy dissipation in a structure. With the RDF-03 design, the majority of the beams are less demanded of plastic deformations. The inelastic responses, after been satisfied the design conditions of each Code, show satisfactory inelastic behavior; this is, according to the determined non-linear responses amplitude determined in this work, it would be enough to design following its recommendations. An combination adequate of lateral resistance and stiffness and ductility should be seek in order to make each structure to behave in an adequate way in front of severe and moderate earthquakes; the subsoil characteristics on which it is going to be located, should be perfectly known, as well as the reinforcement and detailed special requirements of ductile frames should be respected.

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