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Seismic resistant design of building: multinational codes and programs

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ABSTRACT

The objective of this work is to implement the provisions of building codes current in the U.S. as well as those of other countries for the seismic resistant design of buildings. The work includes the implementation of a total of 28 selected building codes. The objective is to assemble in one volume the main provisions of each code followed by the corresponding computer program and illustrative examples for the seismic design of typical buildings. This paper presents a section in this volume corresponding to the implementation of the seismic provisions of the building code used in Spain, La Norma Basica de la Edificacion y Acciones en la Edificacion, NBE-AE-88.

INTRODUCTION

The design of buildings and other structures to resist the effects of earthquakes are generally based on building design codes promulgated for a specific country or region of a country. Building codes are intended to provide guidelines and formulas which constitute minimum legal requirements for design and construction within a particular country or region. These requirements are intended to achieve satisfactory performance of the structure when subjected to seismic excitation.

The objective of the present work is the preparation of a volume containing a description of the seismic codes for countries located geographically in regions of high seismic activity. This work also includes the development of computer programs for the implementation and application of the seismic codes of these countries. To illustrate this undertaken,the main provisions for seismic design of buildings as required by the building code currently in use in Spain is presented and applied to the seismic design of a six-story building.

PROVISIONS OF THE SEISMIC BUILDING CODE OF SPAIN

The Spanish Basic Norm for Building Construction (Ministerio de Obras Publicas y Urbanismo, Madrid, Spain, 1988) establishes that buildings should

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be analyzed under the action of equivalent seismic lateral forces F_i applied statically at discrete mass points located at the floor levels of the building. These equivalent seismic forces are calculated by

$$F_i = s_i\, Q_i \tag{1}$$

in which Q_i are the concentrated weights at the level of the floors and s_i is the seismic coefficient given by the following formula:

$$s_i = \alpha . \beta . \eta_i . \delta \le 0.20 \tag{2}$$

The factors in this equation are designated as follows:

α - intensity factor
β - response factor
η_i - distribution factor
δ - foundation factor

The seismic coefficient s_i, through the factors α, β, η_i, and δ, depends on the fundamental period of the structure which may be determined using exact theoretical procedures or using approximate or empirical formulas provided by the code:

For buildings with structural walls:

$$T = 0.06 \frac{H}{\sqrt{L}} \sqrt{\frac{H}{2L + H}} \ge 0.50 \text{ sec} \tag{3}$$

For reinforced concrete buildings:

$$T = 0.09 \frac{H}{\sqrt{L}} \ge 0.50 \text{ sec} \tag{4}$$

For steel buildings:

$$T = 0.10 \frac{H}{\sqrt{L}} \ge 0.50 \text{ sec} \tag{5}$$

For reinforced concrete buildings with structural walls or with steel bracing, the values for the fundamental period T calculated by the above formulas should be multiplied by the factor f given by

$$f = 0.85 \sqrt{\frac{1}{1 + L/H}} \tag{6}$$

In these formulas H is the height of the building in meters and L the plant dimension (also in meters) in the direction of the seismic forces.

In lieu of a more precise determination for the period of the second mode T_2 and for the third mode T_3, the code provides the following empirical formulas:

$$T_2 = \frac{1}{3} T \geq 0.25 \tag{7}$$

and

$$T_3 = \frac{1}{5} T \geq 0.25 \tag{8}$$

where T is the fundamental period.

a) Intensity factor α

The intensity factor α is established by

$$\alpha = C R \tag{9}$$

where C is the <u>basic seismic coefficient</u> which is equal to the spectral acceleration evaluated for different values of the seismic intensity G as indicated in Table 1 and where R is the <u>seismic risk coefficient</u> given in Table 2.

Table 1. Basic Seismic Coefficient C (NBE-NE-88)

Seismic Intensity G (Grades)	Basic Seismic coefficient C
V	0.02
VI	0.04
VII	0.08
VIII	0.15
IX	0.30

The seismic intensity Grade G is obtained from the seismic zone map provided by the code. In this map, the national territory of Spain has been divided into seismic zones with intensity degrees defined by the International Macroseismic Intensity Scale. The code also provides the correspondence between the seismic intensity Grade G and the spectral velocity S_v. This correspondence is given by

$$S_v = 1.5\,(2)^{G-5}\ (cm/sec) \tag{10}$$

Table 2. Seismic Risk Coefficient (NBE-NE-88)

Seismic Intensity G (Grades)	Seismic Risk R (Period in years)			
	50	100	200	500
VII	1	1	1	1
VIII	0.90	0.99	1	1
IX	0.72	0.92	0.99	1
X	0.53	0.78	0.95	1

b) Response factor β

The response factor β depends on the period of the structure and on its damping characteristics as given by

$$\beta = \frac{B}{\sqrt{T}} \geq 0.5 \qquad (11)$$

in which B = 0.6 for buildings with many internal partition walls and B = 0.8 otherwise. The values for the response factor β for the second and third modes are also calculated with Eq.(11) after replacing the fundamental period T respectively, for the period corresponding to the second and third modes.

c) Distribution factor η_i

For structures modeled with discrete concentrated weights Q_i, the distribution factor η_i corresponding to the level i is given by

$$\eta_i = \frac{\sum_{k=i}^{N} Q_k X_k}{\sum_{k=1}^{N} Q_k X_k^2} \qquad (12)$$

where

N = Number of levels with concentrated weights
X_k = Maximum displacement at level k
Q_k = Concentrated weight at level k

The code provides also simplified formulas to calculate the values of η_i corresponding to the fundamental mode and to second and third modes. These simplified formulas are based on the assumption of linear lateral displacements of the building.

d) Foundation factor δ

The values of the foundation factor δ are given in Table 3 according to the nature of the soil and type of foundation.

Table 3 Foundation factor δ (NBE-NE-88)

Type of foundation 4000	Swamps $C \leq 500$	Loose sands and gravels $500 < c \leq 1000$	Consolidated sands and gravel $1000 < c \leq 2000$	Compact rocks $2000 < c \leq 4000$	Very comp rocks $c > 4000$
		Type of Soil			
Piles:					
Friction type	2.0	1.0	0.7	--	--
Bearing type	1.8	0.9	0.6	--	--
Spread Footing					
Isolated........	1.6	1.1	0.8	0.5	0.5
Continuous....	1.5	1.0	0.7	0.4	0.3
Slabs...........	1.4	0.7	0.5	0.3	0.2

c = velocity of elastic compression wave (meter per second)

e) Overturning moments

The lateral seismic forces produce overturning moments and axial forces in the columns, particularly at the external columns of the building. These overturning moments increase alternatively the gravitational forces in the external columns at one side of the building during the vibration of the structure. The overturning moment at a level of the building is determined as the moment produce at that level by the lateral seismic forces applied at the above levels. Therefore, the overturning moment M_i at the level i of height Z_i is given by

$$M_i = \sum_{k=1}^{N} F_k \, (Z_k - Z_i) \quad for\ i = 0,1,2...(N-1) \qquad (13)$$

where the lateral forces F_k for each mode are calculated by Eq.(1).

f) Story Shear Forces

The shear force V_i at level i, on the resisting elements of story i of the building, is given by the sum of the lateral seismic forces above that level:

$$V_i = \sum_{k=1}^{N} F_k \qquad (14)$$

g) Torsional Moment

Torsional moment M_{ti} at each story is equal to the story shear force V_i multiplied by the eccentricity e_i, the distance between the center of the above mass and the stiffness center of the story. This distance is measured normal to the direction of the seismic forces.

h) Lateral displacement

The lateral displacements at the various levels of the building may be determined by static analysis of the building subjected to the equivalent lateral forces F_i. When the structure is modeled as a shear building with rigid horizontal diaphragms at the floor levels, the relative displacement Δ_i in story i may be evaluated as

$$\Delta_i = \frac{V_i}{K_i} \qquad (15)$$

in which V_i is the story shear force and K_i is the stiffness of the story.

The lateral displacement at level i with respect to the base of the building is then given by the sum of the relative displacements of the lower stories. Therefore, the displacement X_i at the level i is given by

$$X_i = \sum_{j=1}^{i} \Delta_j \qquad (16)$$

Numerical Example

Use is made of a computer program developed to implement the seismic provisions of the Building Code of Spain. The plane steel frame of Fig. 1 serves to model a six-story building. Loads of 20,000 Kp (kilograms weight) are attributed at each level of the building except at the roof where the load is 10,000 Kp. The total flexural rigidity of the columns in any story is EI = 1.3 x 10^{11} Kp-cm^2. The risk period equal to 50 years and seismic intensity G = IX. The building is projected with isolated foundations for the columns in a soil of consolidated gravel and sand.

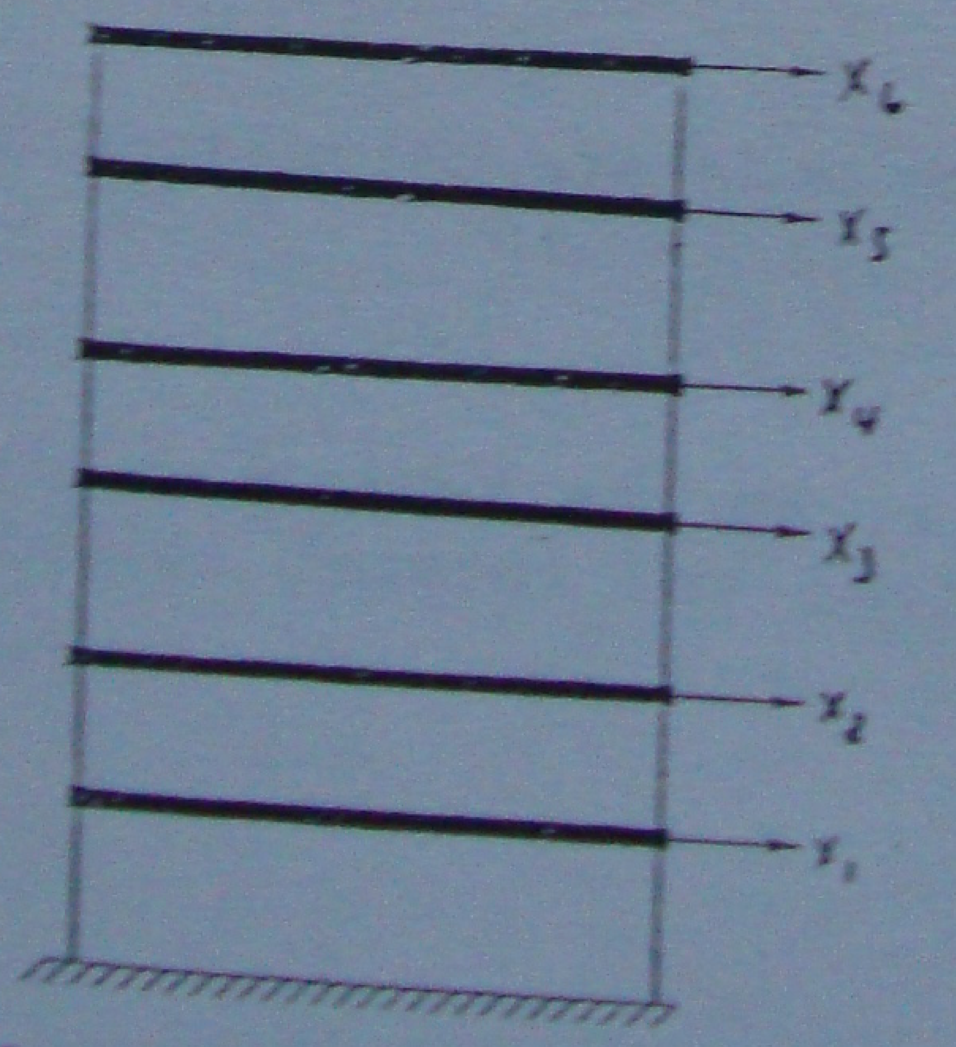

Figure 1 Modeled building for numerical example

INPUT DATA AND OUTPUT RESULTS FOR EXAMPLE

INPUT DATA:

INTENSITY FACTOR	NDI = 9
RISK PERIOD	RI = 50
BASE DIMENSION (EARTHQUAKE DIRECTION) (M)	L = 6
TYPE OF SOIL	NT = 3
FOUNDATION TYPE	NC = 3
NUMBER OF STORIES	ND = 6

FACTORS OF THE SEISMIC COEFFICIENT

FACTOR	MODE 1	MODE 2	MODE 3
INTENSITY FACTOR (ALPHA)	0.080	0.240	0.401
RESPONSE FACTOR (BETA)	0.689	1.194	1.541
FOUNDATION FACTOR (DELTA)	0.800	0.800	0.800

DISTRIBUTION FACTOR, ETA(I,J)

LEVEL	MODE 1	MODE 2	MODE 3
6	1.456	-0.103	0.331
5	1.235	-0.056	0.080
4	1.014	-0.009	-0.170
3	0.794	0.038	-0.240
2	0.573	0.085	0.010
1	0.353	0.075	0.260

SEISMIC FACTOR, S(I,J)

LEVEL	MODE 1	MODE 2	MODE 3
6	0.064	-0.024	0.163
5	0.055	-0.013	0.040
4	0.045	-0.002	-0.084
3	0.035	0.009	-0.119
2	0.025	0.019	0.005
1	0.016	0.017	0.129

RESULTS:

SEISMIC INTENSITY	GI = .3
FUNDAMENTAL PERIOD	T1 = 1.35
SECOND PERIOD	T2 = .45
THIRD PERIOD	T3 = .27
SEISMIC RISK	RS = .72

EQUIVALENT LATERAL FORCES (Kp):

LEVEL	MODE 1	MODE 2	MODE 3	EFFECTIVE FORCE
6	643	-238	1634	1790
5	1092	-259	792	1393
4	897	-43	-1683	1938
3	702	173	-2377	2502
2	507	389	99	621
1	312	346	2575	2616

SHEAR FORCE (Kp):

LEVEL	MODE 1	MODE 2	MODE 3	EFFECTIVE FORCE
6	643	-238	1634	1756
5	1735	-497	2426	2983
4	2632	-540	743	2735
3	3334	-367	-1634	3713
2	3841	22	-1535	4136
1	4153	367	1040	4281

OVERTURNING MOMENT (Kp-m):

LEVEL	MODE 1	MODE 2	MODE 3	EFFECTIVE MOMENT
5	3217	-1188	8169	8780
4	11893	-3672	20300	23527
3	25054	-6372	24013	34703
2	41724	-8208	15844	44631
1	60928	-8100	8169	61473
0	94151	-5162	16487	95584

LATERAL DISPLACEMENTS (cm):

LEVEL	MODE 1	MODE 2	MODE 3	EFFECTIVE DISPL.
6	2.91	-0.12	0.30	2.93
5	2.47	-0.07	0.07	2.47
4	2.03	-0.01	-0.15	2.03
3	1.59	0.04	-0.22	1.60
2	1.15	0.10	0.01	1.15
1	0.71	0.09	0.23	0.74

TORSIONAL MOMENT (Kp-m):

LEVEL	MODE 1	MODE 2	MODE 3	EFFECTIVE MOMENT
6	643	-238	1634	1756
5	1735	-497	2426	2983
4	2632	-540	743	2735
3	3334	-367	-1634	3713
2	3841	22	-1535	4136
1	4153	367	1040	4281

Reference

Ministerio de Obras Publicas y Urbanismo (1988), La Norma Basica de la Edificacion Acciones en la Edificacion, NBE-AE-88, Madrid, Spain.