Annex*
Methods for the Analysis of Structural Vulnerability

Qualitative and quantitative methods of analysis of varying degrees of complexity exist to determine structural vulnerability, depending on the objective.

Qualitative methods use general characteristics to describe the structure. They are generally associated with universal indices that have been calibrated from damage experienced in existing structures, allowing the identification of risk in general terms and, in some cases, the level of damage. Among these methods, those proposed by Hirosawa[1], Gallegos and Rivers[2], Meli[3], Astroza *et al*.[4] and Shiga[5] merit special mention.

The quantitative methods are based on analyses that are not necessarily more precise. Typically they are extensions of the analysis process and current seismic-resistant design recommendations.

As an example of a preliminary assessment, this Annex gives a brief description of a variation of the Hirosawa method that has been used in countries like Chile, Peru, Mexico and Ecuador. The changes introduced make this methodology valid for the construction styles and materials typically used in Latin American countries.

According to this method, structural vulnerability is determined by comparing:

(a) The strength, configuration of buildings, maintenance and previous damages in the building;
(b) The level of seismic demands on performance of structure, representing the seismic hazard and the local conditions of the site where the building is located.

In the case of the Hirosawa method, the comparison is done by calculating two indices and establishing that the building is seismically safe when the index corresponding to the resistance provided for the building (I_S) is greater than the resistance demanded (I_{SO}).

Hirosawa method

The method proposed by Hirosawa is used in Japan by the Ministry of Construction in the assessment of the seismic safety of buildings made of reinforced concrete. The method recommends three lev-

* The technical content of the following annex has been taken from the document *"Análisis de vulnerabilidad y preparativos para enfrentar desastres naturales en hospitales en Chile"*, Universidad de Chile. Study made by PAHO/WHO – ECHO, Santiago, Chile, 1996.

1 Hirosawa, M., *Retrofitting and restoration of buildings in Japan*, IISEE Lecture Note, Seminar Course, Tsukuba, Japan, 1992.

2 Gallegos, H. and R. Ríos, *Índice de calidad estructural sismorresistente*. 4as Jornadas Chilenas de Sismología e Ingeniería Antisísmica, Volume 2, Viña del Mar, Chile, 1986.

3 Meli, R., *Diseño sísmico de muros de mampostería, la práctica actual y el comportamiento observado*, Simposio Internacional de Seguridad Sísmica en Vivienda Económica, CENAPRED, Mexico City, Mexico, 1991.

4 Astroza, M., M.O Moroni and M. Kupfer, *Calificación sísmica de edificios de albañilería de ladrillos confinada con elementos de hormigón armado*. Memorias de las XXVI Jornadas Sudamericanas de Ingeniería Estructural, Vol. 1, Montevideo, Uruguay, 1993.

5 Shiga, T., Earthquake damage and the amount of walls in reinforced concrete buildings. *Proceedings 6th World Conference of Earthquake Engineering*, New Delhi, India, 1977.

els of assessment that go from the simplest to the most detailed. It is based on the analysis of the seismic behavior of each floor of the building in the main directions of the floor plan.

The method was originally proposed for use in existing or damaged buildings made of reinforced concrete and possessing six to eight floors built with walls or porticos. In more recent studies the method has been applied to buildings made of mixed reinforced concrete and masonry.[6]

Structural vulnerability is established according to the following considerations:

(a) If $I_S \geq I_{SO}$ the building will demonstrate seismically safe behavior in case of a seismic event;

(b) If $I_S < I_{SO}$ the building will demonstrate unstable behavior in case of a seismic event and is, therefore, considered unsafe.

Calculation of the I_S index

This index is calculated using the following equation:

$$I_S = E_O * S_D * T$$

where:

E_O: is the basic seismic index of structural behavior,

S_D: is the index of structural configuration, and

T: is the index of deterioration of the building.

Calculation of E_O

When applying the first level of assessment, the Eo index is determined by the simple calculation of the absolute shearing strength of each floor. This resistance is calculated for each direction of the floor plan by the sum of the product of the area of the cross-section of a wall or column and its shearing strength. This product is then reduced by a factor (α_i) that represents the presence of elements that reach their resistance to a level of deformation that is less than that of the rest of the seismic-resistant elements (e.g., short columns or masonry walls, either reinforced or not, when compared with reinforced concrete walls or columns).

The E_O index is proportional to the product of the resistance coefficient (C) and ductility coefficient (F).

$$E_O \alpha C * F$$

For the calculation of E_O, all elements or vertical substructures that form part of the seismic-resistant building must be classified under one of the following categories:

i. Short reinforced concrete columns. These are all the columns in which the h_O/D ratio—between the vertical clearance (h_O) and the width of the cross-section (D)—is equal or less than 2. The seismic behavior of these columns is controlled by shearing failure characterized by the low level of resistance to deformation and by the low capacity of inelastic deformation. In order to establish the vertical clearance, due account was given to the presence of architectural elements that reduce the height of the column (i.e., elements that are not isolated from the column).

6 Iglesias, J., The Mexico Earthquake of September 19, 1985 – Seminar zoning of Mexico City after the 1985 earthquake, *Earthquake Spectra*, Vol. 5, No1, 1989.

ii. Reinforced concrete columns. These are all the columns in which the h_o/D ratio is greater than 2.
iii. Reinforced concrete walls. These are the reinforced concrete elements with a cross-section in which the relation between the larger side and the smaller side of the cross-section is greater than 3.
iv. Infilled brick walls. These are brick walls, normally with little or no reinforcement, located in openings of the resistant substructure (porticos) without being isolated from them.
v. Reinforced brick walls or brick walls confined with thin elements of reinforced concrete, pillars and framing.

The above-mentioned walls correspond to those that have been designed and constructed in order to transmit horizontal and vertical loads from one level to a lower level and to the foundation. Walls that merely resist loads ensuing from their own weight are not considered, including infilled parapets and partitions or dividing walls that are isolated from the seismic-resistant structure.

This classification must be made to determine resistance and to address the smaller capacity for inelastic deformation and capacity for energy dissipation that some elements display (for example, the short columns and unreinforced, infilled brick walls when they control performance).

The E_o index is calculated by means of the following equation:

$$E_p = \frac{(n_p + 1)}{(n_p + i)} * \{ \alpha_1 * (C_{mar} + C_{sc} + C_a + C_{ma}) + \alpha_2 * C_w + \alpha_3 * C_c \} * F$$

where:

α_1: reduction factor of the resistant capacity in accordance with the deformation level at which the elements that control seismic behavior resist.[7] The values of these factors are given in table A1 when the seismic capacity is controlled by the weakest elements (Type A), less weak elements (Type B) and ductile elements (Type C), respectively

N_p: number of floors in the building

i: the level under assessment

C_{mar}: the resistance index exhibited by the infilled brick walls

C_{sc}: the resistance index exhibited by the short reinforced concrete columns

C_a: the resistance index exhibited by the unreinforced or partially confined brick walls

C_{ma}: the resistance index exhibited by the confined brick walls

C_w: the resistance index exhibited by the reinforced concrete walls

C_c: the resistance index exhibited by the reinforced concrete columns that are not short

F: the ductility index associated with the vertical elements

F = 1.0 if C_{mar}, C_a and C_{sc} are equal to zero

F = 0.8 if C_{mar}, C_a and C_{sc} are not equal to zero

In case the confined brick walls control the resistant capacity, the value of F is equal to 1.0 considering the capacity for inelastic deformation that is obtained with the confining elements.

[7] Murakami, M., K. Hara, H. Yamaguchi, S. Shimazu, Seismic capacity of reinforced concrete buildings which suffered the 1987 Chibaken-toho-oki earthquake, *Proceedings 10th World Conference of Earthquake Engineering*, Madrid, Spain, 1992.

Seismic capacity must be calculated first by considering the failure of the weakest elements. Nevertheless, if the failure of this group does not produce instability in the system, seismic capacity must be calculated by considering the next group and rejecting the resistance of the elements that have failed.

Table A1.
Values of the coefficients α_i

Type	α_1	α_2	α_3	Failure
A	1.0	0.7	0.5	Infilled brick walls or short columns or non-reinforced and partially confined brick walls or confined brick walls control failure.
B	0.0	1.0	0.7	Reinforced concrete walls control failure.
C	0.0	0.0	1.0	Reinforced concrete columns control failure.

The term (n + 1)/(n +i) refers to the relation between the coefficient of basal shearing and the coefficient of shearing of floor i, when these shearing forces are established as a function of the weight of the building divided by the level being considered.

The resistance indices (C_i) were determined based on the strengthening characteristics of the reinforced concrete walls constructed in Chile (quantity and means of reinforcement), which incorporates changes in the figures proposed by Hirosawa and Iglesias. For the brick walls, the resistance proposed by Iglesias for infilled walls (diaphragm-type walls) and the resistance of diagonal cracking recommended by Raymondi[8] for confined brick walls were utilized.

The equations used were:

$$C_{mar} = \frac{0.6 * 0.85 * \tau_o * \sum A_{mar}}{\sum_{j=i}^{n_p} W_j}$$

$$C_{sc} = \frac{f_c}{200} * \frac{15 * \sum A_{sc}}{\sum_{j=i}^{n_p} W_j}$$

$$C_{mar} = \frac{0.6 * (0.45 * \tau_o + 0.25 * \sigma_o) * \sum A_{ma}}{\sum_{j=i}^{n_p} W_j}$$

8 Raymondi, V. , *Anteproyecto de norma de diseño y cálculo de albañilería reforzada con pilares y cadenas*, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile, 1990.

$$C_a = C_{ma}$$

$$C_w = \frac{f_c}{200} * \frac{30 * \sum A_{m_1} + 20 * \sum A_{m_2} + 12 * \sum A_{m_3} + 10 * \sum A_{m_4}}{\sum_{j=i}^{n_p} W_j}$$

$$C_c = \frac{f_c}{200} * \frac{10 * \sum A_{c_1} + 7 * \sum A_{c_2}}{\sum_{j=i}^{n_p} W_j}$$

where:

f_c = Cylindrical resistance to compression exhibited by the concrete.

$\sum A_{mar}$ = Sum of the areas of the infilled brick walls on the floor under assessment in the direction under analysis.

$\sum A_{sc}$ = Sum of the area of short reinforced concrete columns on the floor under assessment.

$\sum A_{ma}$ = Sum of the areas of the confined brick walls on the floor under assessment in the direction under analysis.

$\sum A_{m_1}$ = Sum of the areas of the reinforced concrete walls on the floor under assessment with columns in both ends, with horizontal reinforcement greater than or equal to 1.2 % and wall thinness (HIL) greater than 2. In these walls the resistance to shearing is controlled by the resistance to crushing of the compressed diagonal due to the high level of horizontal reinforcement.[9]

$\sum A_{m_2}$ = Sum of the areas of the reinforced concrete walls on the floor under assessment with columns in both ends and a minimal amount of horizontal reinforcement. In these walls the resistance to shearing is provided mainly by the horizontal reinforcement.[10]

$\sum A_{m_3}$ = Sum of the areas of the reinforced concrete walls on the floor under assessment, without columns or with a column in some of its ends, a wall thinness less than or equal to 2 and minimum reinforcement. In these walls, the resistance to shearing is defined by the diagonal cracking load of the concrete due to its reduced level of reinforcement.[11]

$\sum A_{m_4}$ = Sum of the areas of the reinforced concrete walls on the floor under assessment, without columns or with a column in some of its ends and a wall thinness greater than 2. In these walls the resistance to shearing is provided by the ACI-318 standard equations.[12]

---

9 Wakabayashi, M., *Design of earthquake-resistant buildings*, Mc Graw-Hill Book Company, 1986.

10 Ibid.

11 Ibid.

12 ACI 318 (1984) "Building Code Requirements for Reinforced Concrete."

$\sum A_{c_1}$ = Sum of the areas of the reinforced concrete columns[13] where the relation between the vertical clearance (h) and the width (D) is less than 6.

$\sum A_{c_2}$ = Sum of the areas of the reinforced concrete columns[14] where the relation between the vertical clearance (h) and width (D) is equal to or greater than 6.

W_j = Weight of floor j.

τ_o = Basic resistance to shearing of masonry.

σ_o = Normal stress due to axial force produced by the weight of vertical loads and overloading.

L = Length of the wall.

H = Height of the floor if L is greater than or equal to 3 m, or the vertical clearance of the wall if L is less than 3 m.

In these equations the areas must be expressed in cm^2, the resistance and stress in kgf/cm^2 and weight in kg. The coefficients that accompany the areas correspond to the resistance to shearing exhibited by the different types of elements that form the seismically resistant system. The value of these coefficients is expressed in kgf/cm^2.

Calculation of S_D

This coefficient quantifies the influence of irregularities in the structural configuration and the distribution of stiffness and mass on the seismic behavior of the building.

Information needed to calculate S_D is obtained mainly from structural plans and is complemented by on-site visits. The characteristics of a building considered in the determination of this coefficient are: regularity of the floor plan, the length-width relation of the floor plan, contraction points in the floor plan, thickness of the expansion joints, dimensions and location of inner patios, existence of a basement, uniformity of height of the floors, eccentricity in the stiffness of the floor plan, irregularities in the distribution of mass, stiffness of the mezzanine of higher floors, etc.

Hirosawa proposes the following equation to calculate S_D when the first level of assessment of vulnerability is used:

$$S_D = \prod_{i=1}^{1=8} q_i$$

where:

$$q_i = \{1.0 - (1 - G_i) * R_i\} \; when \; i = 1, 2, 3, 4, 5, 7 \; and \; 8$$

$$q_i = \{1.2 - (1 - G_i) * R_i\} \; when \; i = 6$$

The values of G_i and R_i recommended by Hirosawa are shown in table A2.

13 Hirosawa, M. (1992) "Retroffiting and Restoration of Buildings in Japan" IISEE, Lecture Note of Seminar Course, Tsukaba, Japan.

14 ACI 318 (1984) “Building Code Requirements for Reinforced Concrete”.

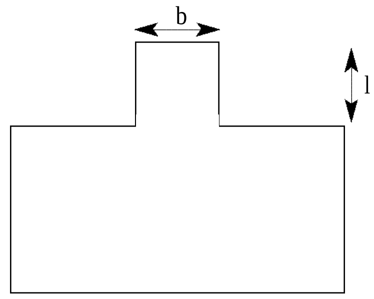
Table A2.
Values of Gi and Ri

ITEMS (q_i)	G_i			R_i
	1.0	0.9	0.8	
1.Regularity	Regular (a_1)	Median (a_2)	Irregular (a_3)	1.0
2.Length-width ratio	$B \leq 5$	$5 < B \leq 8$	$B > 8$	0.5
3.Contraction of the plan	$0.8 \leq c$	$0.5 \leq c \leq 0.8$	$c < 0.5$	0.5
4.Vestibule or interior patio	$R_{ap} = 0.1$	$0.1 < R_{ap} \leq 0.3$	$0.3 < R_{ap}$	0.5
5.Eccentricity of the vestibule or interior patio	$f_1 = 0.4$ $f_2 = 0.1$	$f_1 \leq 0.4$ $0.1 < f_2 \leq 0.3$	$0.4 < f_1$ $0.3 < f_2$	0.25
6.Basement	$1.0 \leq R_{as}$	$0.5 \leq R_{as} < 1.0$	$R_{as} < 0.5$	1.0
7.Expansion joint	$0.01 \leq s$	$0.005 \leq s < 0.01$	$s < 0.005$	0.5
8.Uniformity of height of floor	$0.8 \leq R_h$	$0.7 \leq R_h < 0.8$	$R_h < 0.7$	0.5

Following is the description of each one of the characteristics.

1. Regularity a_i

a_1: The floor plan is symmetrical in each direction, and the area of projections is less than or equal to 10% of the total area of the plan. These projections are considered where $l/b \geq 0.5$.



a_2: The plan is irregular, and the area of projections is less than or equal to 30% of the total area of the plan. This includes plans with L, T, U, and other shapes.

a_3: The floor plan is more irregular than in a_2, and the area of projections is greater than 30% of the area of the floor plan.

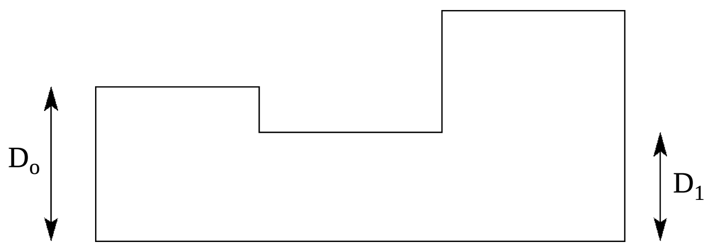
2. Length-width ratio, B:

Ratio of the greater and lesser dimensions of the floor plan.

In floor plans of type L, T, U and others, the longer side is considered 2*l, with l shown in the figure below.

3. Contraction of the floor plan, c:

$$c = \frac{D_1}{D_o}$$



4. Vestibule or inner patio, R_{ap}:

This is the ratio of the area of the vestibule or patio to the total area of the plan, including the area of the patio/vestibule. Nevertheless, a flight of stairs constructed with reinforced concrete walls is not considered in this analysis.

5. Eccentricity of vestibule or inner patio, *f*:

f_1: Ratio of the distance from the center of the floor plan to the center of the vestibule, and the shorter length of the floor plan.

f_2: Ratio of the distance from the center of the floor plan to the center of the vestibule, and the greater length of the floor plan.

6. Basement, R_{as}:

Ratio of the mean area of the floor plan of the basement levels to the mean area of the building's floor plan.

7. Expansion joints, *s*:

This criterion is applied to buildings that have expansion joints. It is the ratio of the thickness of the seismic expansion joints to the height where the joints are located.

8. **Uniformity of height of floor, R_h:**
Ratio of the height of two contiguous floors (height of the floor above the floor under analysis to the height of the floor being considered). For the case of the highest floor, the floor immediately above in this ratio is replaced by the floor immediately below.

According to Hirosawa, the value of S_D is calculated by using the least favorable value among those obtained for the characteristics of different floors, a value that is assumed to be representative of the entire building.

Calculation of T

This index quantifies the effects produced by the deterioration of the building over time, effects of previous earthquakes or other events. The index is calculated from information obtained from on-site visits and from the information provided by the owner.

The index T is determined using table A3. When a unique value for T is used for the building, this value must correspond to the smaller value obtained in table A3.

Table A3.
Values of the index T for different causes and types of deterioration

Permanent deformation (T_1)	
Characteristics	**T_1**
The building is leaning due to differential settling	0.7
The building is constructed on landfill	0.9
The building has been repaired due to previous deformations	0.9
Visible deformation of beams or columns	0.9
Does not exhibit any signs of deformation	1.0

Cracks in walls or columns due to corrosion of the reinforced steel (T_2)	
Characteristics	T_2
Signs of leaking with visible corrosion of reinforcement	0.8
Visible slanted cracks in columns	0.9
Visible cracks in walls	0.9
Signs of leaking but without corrosion of reinforcement	0.9
None of the above	1.0

Fires (T_3)	
Characteristics	T_3
It has undergone fire but was not repaired	0.7
It has undergone fire and was suitably repaired	0.8
Has not undergone fire	1.0

Use of the body or block (T4)	
Characteristics	T4
It stores chemical substances	0.8
Does not contain chemical substances	1.0

Type of structural damage (T_5)	
Characteristics	T_5
Severe structural damage	0.8
Major structural damage	0.9
Slight structural damage or nonstructural damage	1.0

The criterion for the classification of earthquake damage is shown in table A4.

Table A4.
Classification of damages caused by earthquake

Type of damage	*Description*
Non-structural	Damage only in non-structural elements
Light structural damage	Cracks less than 0.5 mm wide in reinforced concrete elements. Cracks less than 3 mm wide in masonry walls
Major structural damage	Cracks 0.5 to l mm wide in reinforced concrete elements. Cracks 3 to 10 mm wide in masonry walls.
Severe structural damage	Cracks more than 1 mm wide in reinforced concrete elements. Openings in masonry walls.Collapse of concrete, breakage of stirrups and buckling of reinforcement in beams,columns and walls of reinforced concrete.
Cracking of capitals and consoles	Collapse of columns.Collapse of more than 1% of building height.Building settles more than 20 cm.

Source: Iglesias,J.,The Mexico Earthquake of September 19,1985 – Seminar zoning of Mexico City after the 1985 earthquake, *Earthquake Spectra*,Vol.5,No1,1989.

Calculation of index I_{SO}

This index is calculated using the following equation:

$$I_{so} = E_{so} * Z * G * U$$

where:

E_{SO} = Required basic seismic resistance

Z = Seismic zone factor; its value depends on the seismic hazard of the place where building is located ($0.5 \leq Z \leq 1$)

G = Influence of the topographical and geotectonic conditions

U = Importance of building according to its use

Basic seismic resistance (E_{SO}) was determined based on the study of building damage during an earthquake.[15] For the purpose of other studies, it is recommended that this resistance be established based on requirements for elastic strength under the current norms in the greatest seismic hazard zone (epicenter), reduced by a factor of reduction (R) whose value must be determined given that the damage does not impede function of the facility.

Factor G is equal to 1.0 for topographical conditions without slope, and is equal to 1.1 for zones with slope.[16]

The importance factor, U, is equal to 1.0 given that the required conditions for use of the building are considered when establishing the value of E_{SO}.

15 Hirosawa, M., "Retrofitting and Restoration of Buildings in Japan". IISEE Lecture Note, Seminar Course, Tsukuba, Japan, 1992.

16 Ibid.