SEISMIC VULNERABILITY OF SCHOOL BUILDINGS IN TOLUCA CITY

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SUMMARY

A methodology to estimate the seismic vulnerability of masonry walls and reinforced concrete frame structures is presented, this procedure is divide in two steps. In the first part of the study a simplified evaluation technique was used, in which the behavior of the building was represented by the ratio of the base shear force acting at failure to the shear resistance force, for those constructions in which the expected behavior is not acceptable, a more accurate methodology is applied, in this case the behavior of the construction during an expected earthquake is estimated as a function of the damages in the building due to the story drift.

This methodology is being applied to determinate the seismic vulnerability of school buildings in Toluca, Capital City of State of Mexico, which is located in the central region of Mexico in a moderate seismic risk zone.

INTRODUCTION

As a part of the vulnerability study of Toluca City where 859 masonry buildings and 57 reinforced concrete buildings were evaluated, now the seismic vulnerability in school buildings is presented, considering just masonry and reinforce concrete structural systems.

Public school buildings in Toluca City and Metepec were visited to determinate their geometry and structural properties, after this a methodology of evaluation for each structural system was applied, using the regulations of Mexico City Code [12] to estimate the shear resistance and supposing construction local practices as well as mechanical characteristics of materials used.

FIRST EVALUATION TECHNIQUE

The purpose of this inspection is to estimate the structural behavior of a construction based on a fast evaluation technique. The identification of the structural system, the geometry of the construction and the general characteristics of the building are required in this step.

This simplified evaluation was developed for masonry structures and reinforced concrete frame structures.

MASONRY STRUCTURES

The evaluation method for masonry building composed by confined masonry with reinforced concrete elements and walls formed by bricks or light concrete blocks are considered. This methodology is limited to structures with less than four story levels, regular elevation and ground plant.

The lateral resistance of walls can be estimate as [12]

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$$V_r = F_r\,(0.5\,v^*\,A_T + 0.3\,P) \qquad (1)$$

Where:

Vr = Shear resistance force

Fr = Resistance factor

v* = shear stress

A_T = Transversal wall area

P = Vertical force acting on the wall

Neglecting the contribution of vertical force, the total shear force supported by the walls in one direction is:

$$\Sigma V_r = F_r\,(0.5\,v^*\,\Sigma\,A_T\,) \qquad (2)$$

Considering:

F_r = 0.7 (to confined walls)

v* = 3 kg/cm2

A = 1200L (walls of 12 cm thickness, and L the wall longitude expressed in meters.)

$$\Sigma V_r = 0.7\,(0.5x\;3x1200\;SL) = 1260\,\Sigma L \qquad (3)$$

In the above equation, the walls which ratio between high floor and longitude is minor or equal to 1.33 will not be taken in account.

To evaluate the seismic actions on the structure, its weight was estimated, the proposed loads are:

Table 1: estimated weights for masonry buildings

	Dead load	Live load	Total
Floor	423	350	773
Flat	408	100	508

The base shear force for a structure with area A, number level N, seismic coefficient c=0.2 and seismic behavior factor Q = 2 is:

$$Vu = (71.5\,N - 11)A \qquad (4)$$

Finally the structure behavior is obtained with the ratio between shear resistance and acting shear wrote as:

$$Io = \Sigma\,Vr / Vu = \Sigma\,L / (0.0667\,N - 0.0087)A = \Sigma\,L / 0.053\,NA \qquad (5)$$

REINFORCED CONCRETE STRUCTURES

This methodology is focused to structures formed by rigid frames (beam and column) regulars on flat and elevation and height lesser than 15 m.

The shear resistance on a rectangular column is (x):

$$V_r = (F_r\,A_v\,f_y\,d)/s + V_{cr} \qquad (6)$$

Where:

V_r – Shear resistance force

F_r - Reduction factor equal to 0.8

A_v – area of the web reinforcement

d – effective depth

s – tied separation

V_{cr} – Concrete shear force, given by:

$$Vcr = 0.5x0.8xAc\,(0.8\,f'c)^{1/2} \qquad (7)$$

For a longitudinal steel ratio up to one percent (common value in columns), where:

Ac = column transversal area

f´c= concrete compressive strength

Considering construction techniques and design practice, the typical values are: f´c= 200 kg/cm^2, fy = 4200 kg/cm^2, Av = 0.63 cm^2, s = 0.5d, then the shear resistance is given by:

$$Vr = 4233.6 + 5.06 Ac \quad (8)$$

Assuming shear failure on first floor columns and supposing that resistance against lateral loads is supported by concrete columns, the total shear force in the structure will be:

$$\Sigma V r = 4233.6 Nc + 5.06 \Sigma Ac \quad (9)$$

Where

Nc – number of columns in the structure

In the other hand, to estimate shear acting force, the next loads are adopted.

Table 2: estimated weights for reinforced concrete buildings

Dead Load (kg/cm^2)	Live Load (kg/cm^2)	Total (kg/cm^2)
423	350	773

The base shear force in a structure with ground plan A, number of levels N, seismic coefficient c= 0.2 and behavior seismic factor Q = 2 is:

$$Vu = 74.8 NA \quad (10)$$

Finally the ratio between shear resistance force and acting shear is :

$$Io = \Sigma Vr / Vu = (4233.6 Nc + 5.06 \Sigma Ac) / 74.8 NA \quad (11)$$

CORRECTION FACTORS

In case that the structures do not allow to supposed hypothesis on the previous points, a result adjusting will be make, but due to the massive character of this methodology, a simplification way using a corrective factor to qualify the comparative behavior of a structure to do the last requirements will be used.

This point contains the next aspects:

1. Elevation regularity and symmetry ground plan
2. Structuring
3. Conservation

The corrective factor was defined as:

$$K = k_1 \times k_2 \times k_3 \quad (12)$$

Where:

k_1 – Corrective factor to asymmetry on ground plan and elevation

k_2 – Corrective factor to deficient structuring

k_3 – Corrective factor to deterioration

ki values are given by:

Table 3: Corrective factors.

Concept	Good	Regular	Bad
Regularity	1.0	0.9	0.8
Structuring	1.0	0.9	0.8
Conservation	1.0	0.9	0.8

Finally the structure behavior is determined by the product of the index (Io) per corrective factor

$$I = Io\ K \tag{13}$$

The conclusion obtained is as follows:

I >= 1.0 The structure is according the requirements of the regulations, is considering like a safe place for the seismic coefficient adopted.

0.73 < I < 1.0 When the structure is up of the service solicitations but not satisfied the design criteria, it means the load and resistance factors are not according the regulations. More accurate evaluation is recommended.

I < 0.73 When the structure resistance is lower than the service solicitations, then the behavior is consider risky.

For those constructions in which 0.73 < I < 1.0 a more accurate evaluation technique is proposed.

SECOND EVALUATION TECHNIQUE

The proposed methodology is based on the estimation of the building's behavior during a possible earthquake as a function of the expected story drift in each level of the construction. The story drifts are determinate using the dynamic properties of the structure obtained by ambient vibration measurements.

Lateral Displacements in Buildings.

In this part a simplified procedure for estimate lateral displacements that a building may present during a ground motion is proposed.

For a one degree of freedom system subject to a base motion history, the equation of motion could be expressed as:

$$m\ddot{u} + c\acute{u} + ku = - m\ddot{u}g \tag{14}$$

whit:

m - system mass

c - damping coefficient

k - system stiffness

u - mass displacement

In the case of specific earthquake, the displacement *(u)* could be estimated using a displacement spectra, however, for specific cases it is difficult to define a displacement spectra which involve the seismicity parameters for the zone in' which the structure is constructed. An altemative procedure is to estimate the lateral displacement of the building using a design spectra.

The design spectra consider some aspects as local seismicity, regional amplifications, and in some way they involve the security level that one society could accept, then if we satisfy the design spectra, the security level of the construction can be considered suitable for the particular place.

The design spectra ordinate can be defined as:

$$a(T)=w2Xmax/g \tag{15}$$

Where:

a(T) - spectra ordinate

w - circular frequency of the system

Xmax - maximum displacement

g - acceleration of gravity.

From this equation, we can express the maximum displacement as:

$$Xmax = a(T)\, g/w2 \tag{16}$$

For multi degree of freedom systems the equation of motion could be formulated as:

$$M\{\ddot{u}\} + C\{\acute{u}\} + K\{u\} = -M\{l\}\, \ddot{u}_g \tag{17}$$

Where:

M - mass matrix

C - damping coefficient matrix

K - stiffness matrix

(ü}, {ú} y *(u}* - acceleration, velocity and displacement vectors respectively

$\ddot{u}_g$ - ground acceleration.

Expressing the structure displacements as:

$$\{u\} = \Phi(y\} \tag{18}$$

With:

Φ- modal shapes matrix

{y} - modal coordinates vector

and substituting eq.5 in eq.4, the equation of motion could be expressed as:

$$\underline{M}\{\ddot{y}\} + \underline{C}\,\{\acute{y}\} + \underline{K}\,\{y\} = -\,\Phi^{T}\, M\,\{1\}\, \ddot{u}_g \tag{19}$$

Where:

$\underline{M}$ - generalized mass matrix

$\underline{C}$ - generalized coefficient matrix

$\underline{K}$ - generalized stiffness matrix.

Dividing the eq.6 by the generalized mass matrix, the equation of motion could be expressed as:

$$yi + 2\,\xi i\;\; wiyi + wi^2 yi\;\; = -\Gamma\, i\, \ddot{u}_g \tag{20}$$

Whit:

ξi - damping ratio

wi- circular frequency of ith mode

Γi- earthquake excitation factor for the ith mode.

If we assume that only the first mode contribute to the structure response arid considering this modal shape normalized whit a unitary displacement at the top level of the building, we have:

$$y + 2\xi wy + w^2\, y = -\Gamma\, \ddot{u}_g \tag{21}$$

In which (y) represents the lateral displacement at the top level. If we want to get the maximum top displacement , we can follow the same criteria that in the one degree of freedom systems, getting the maximum response from design spectra as:

$$ymax= \Gamma[a(T)g/w2] \quad (22)$$

Where:

ymax - maximum displacement at the top level of the building

a(T) - design spectra ordinate corresponding to the natural period (T)

w2 - circular frequency for the 1 st mode

Γ- earthquake excitation factor, given by:

$$\Gamma= \{\Psi\}^T M\{1\}/ \{\Psi\}^T M\{\Psi\} \quad (23)$$

Whit:

M - mass matrix

Ψ- modal shape for the 1 st mode.

The story drift could be estimated from the maximum lateral displacement given by:

$$\{u\} =ymax\{\Psi\} \quad (24)$$

Determination Of Dynamic Properties of a Structure.

To determinate the story drift following the last procedure, we need to know the weight of the structure in each level, the fundamental period for the first mode and the modal shape associate to this period.

Using traditional analysis procedures, it requires a detailed survey of building and a close idea of the mechanical properties of materials that conform the structure. Like an alternative way we can determinate the dynamic properties of a structure with the help of ambient vibrations measurements.

Ambient vibration measurements have been a useful tool to determinate with reasonable precision the dynamic properties of a structure, this technique is based on the microtremors records analysis. This methodology allows to determinate with reasonable precision modal circular frequencies of the structure, modal shapes, damping ratio values, etc. in this way this technique represents a suitable alternative to determinate the dynamic properties of a building, because we can get a good idea about the dynamic behavior of the construction and with less time and work compared against traditional analysis methods. The principal disadvantage of this technique is the cost of the equipment.

Structural Expected Damage Level.

The expected damage in a building, depends mainly of the story drift, the materials quality, the structural system arid the construction details of the different components and it's connections. The present work is limited to analyze the acceptable story drift for reinforce concrete frame structures whit or without masonry or concrete walls.

It is important to note that it is convenient to separate the expected damages in a building during an earthquake event, this damages can be separated into structural damages and non structural damages.

The nonstructural damages do not compromise the structural stability but they affect the functionality of the building. When the main structure is connected with the nonstructural elements it is recommended to limited the story drift to 6% of the story high for avoid nonstructural damages.

When the non structural elements are connected with the main structure and the story drift is bigger than 6% of the story high, damages in this elements are expected. The damage level depends of the ductility of the structural system and the stiffness of nonstructural elements, for that,, the brick nonstructural walls will be the first elements whit damages, followed by glasses and fragile covers.

In the case of structural elements, some experimental studies report that the brick masonry walls adequately reinforced show their first cracks at story drift near to 0.002, however the maximum resistance is reach at story drift near to 0.006, for this deformation level there are considerable amount of cracks but the resistance is maintained for major deformations.

For concrete walls with conventional reinforce and with flexion failure, the first cracks begin for story drift near to 0.003, but generally the element is able to accept deformations bigger than this without a resistance losses, nevertheless when the wall fails in shear, the resistance decrease rapidly for story drift up to 0.005.

The reinforce concrete frames with reasonable constructions details could accept story drift deformation near to 0.02 without severe damages, however it is recommended to limit the story drift to a maximum value of 0.012.

Evaluation Methodology

To estimate the building behavior during an expected seismic movements, the next methodology is proposed:

1. To determinate using ambient vibration, the natural period of fundamental mode of the structure and its associated modal shape normalized whit a unitary displacement at the top level of the building.
2. To estimate the weight on each level of the structure.
3. To determinate the maximum drift at the top level using eq.9.
4. To estimate lateral deformation of each level with the eq. 11 from this values to calculate the story drift on each level. (Δ 1)
5. To calculate the damage index for each level (Idi) like:

$$Idi = (\Delta p) / (\Delta i) \qquad (25)$$

where:

Idi - Damage index on level i

Δi- Story drift at level i

Δ p - permissible story drift

The permissible story drift for different structural systems are shown in table 4.

Table 4. Permissible story drift values

Type of structure	Permissible story drift (Δp)
Concrete frames linked to non structural elements	0.006
Concrete frames with masonry or concrete walls	0.006
Reinforced Concrete frames	0.012

6. To estimate the structural behavior using the next criteria:

Values of Id> 1.0 The structure can be considered like safety

Values of Id < 1.0 It is required to improve the structural behavior.

Limitations.

The purposed methodology is not apply to structures formed by reinforced concrete frames with or without masonry walls or reinforced concrete walls, that should have regular ground plan and elevation, and medium or short high.

This limitations are fixed because the methodology do not take in account the participation of superior modes and neither torsion modes. However we consider that this technique could be modified to overcome this limitations.

CONCLUSION

The purposed methodology allows to estimate on a quick way the behavior of structures against seismic demands contained on design codes, using the design spectra for the zone in which the building is located. The first evaluation method permits to select those structures without problems, and those with severe problems, for the constructions in other cases the second method permit easily get a better idea of its expected behavior.

This evaluation technique has been applied to estimate the vulnerability of school buildings in Toluca City, at this time a total of 77 structures were evaluated, 3 of them were considered risky.

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