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THE NEW MEXICO CITY BUILDING CODE REQUIREMENTS FOR DESIGN AND CONSTRUCTION OF MASONRY STRUCTURES

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Abstract

Most significant modifications to the Mexico City Building Code Requirements for Masonry Structures are discussed. Changes are largely based on analytical and experimental research programs, and field observations conducted in Mexico. During the revision process, emphasis was given to simplify and clarify the requirements; figures were added. A major editorial overhaul of the standards was undertaken. The contribution of horizontal reinforcement and steel welded wire meshes to wall shear strength is now explicit and quantifiable. New requirements for detailing, inspection and quality assurance, and for evaluation and rehabilitation of existing structures are included. A new acceptance criterion for masonry systems different from those accepted in the design standards, and to be subjected to earthquake-induced forces, was included.

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Introduction

In Mexico, building codes should be issued by each municipality. Because there are over 2400 municipalities in the country, the number of potential building codes is, therefore, immense. However, due to economic and technical limitations, few municipalities have issued their own codes. Among them, the Mexico City Building Code (MCBC) is the most comprehensive and advanced set of requirements, and is used as a model code in most regions of the country. The MCBC comprises a group of technical norms on different types of loadings (wind and earthquake) and on structural systems and materials (masonry, steel, concrete, timber, foundations).

As part of the 2002 revision of MCBC, the code requirements for the design and construction of masonry structures (NTC-M) were updated. Such requirements are of utmost importance because over 70 percent of buildings in the country is made of masonry walls. Walls are typically used as load-bearing elements, intended to resist both the vertical and lateral actions. Masonry walls are also heavily used as infills in reinforced concrete and steel frame structures. Masonry is most widely used for housing, especially in low-cost housing.

Masonry requirements, based on allowable stresses, were included in the first version of the MCBC in 1942. In 1976, the MCBC adopted a limit-state design format and included design material strengths and stiffnesses that were obtained from a comprehensive experimental research program carried out at the times. After the 1985 Mexico City earthquakes, NTC-M were revised and updated. Strength reduction factors were slightly increased to reflect the excellent performance of well-designed and well-constructed masonry structures, as well as to counteract the increase in the design seismic shear coefficient adopted in the code.

In recent years, design and construction professionals, material producers, as well as academics, had complained about the complex layout of NTC-M, the ambiguity of several requirements, and the lack of guidance in certain cases. To simplify and clarify NTC-M, a major editorial overhaul was undertaken and an ample number of figures was added. Figures are intended to illustrate important concepts, or those requirements that were deemed as a source of confusion. Also, recent experimental and analytical research results, and field observations on masonry behavior, especially in Mexico, were considered. The intent of this paper is to present the most significant changes made in the last revision of NTC-M (2002).

Materials in NTC-M 2002

Masonry Units and Mortar

Solid and hollow masonry units, either handmade or industrialized, are allowed. Handmade solid clay bricks, industrialized hollow clay bricks (with two cells and multiperforated) and semi-industrialized hollow concrete units are the most commonly used.

In the last decade, multiperforated industrialized clay bricks have become well accepted in low-cost housing, particularly because of their cost (Alcocer 1999). The unit is typically used in combination of hollow units with two cells. In tests and in the field, it has been observed that its typical mode of failure under large cyclic lateral displacements is quite brittle, and is characterized by a sudden crushing and spalling of their exterior walls. To avoid such types of failures, NTC-M 2002 limits the minimum thickness of the exterior wall of the unit to 15 mm, and the minimum net area to 50 percent. Also, only hollow units with vertical perforations are allowed for structural purposes. That latter requirement intends to avoid the catastrophic failures observed in masonry walls in the 1999 Colombia and Turkey earthquakes (EERI 2003, 2000).

Joint mortar shall be proportioned by volume and shall be a combination of Portland cement, lime and sand (PC:L:S). For structural purposes, three types of mortar are recommended: Type I (1 : 0 to ¼ : S) with a cube strength $f_j^* \geq 12.5$ MPa; Type II (1 : ¼ to ½ : S) with $f_j^* \geq 7.5$ MPa, and Type III (1 : ½ to 1¼ : S), where $f_j^* \geq 4$ MPa. In all cases, Portland cement shall be used and the volume of sand S shall be between 2.25 and 3 times the sum of the volumes of Portland cement and lime.

Mechanical Properties

Differently from other building codes, material design properties adopted in the MCBC correspond to a 98 fractile. The reason for this value is the large variation of material properties, as well as the lax quality control procedures in the Mexican construction industry. Three types of design strengths are used in NTC-M 2002: the unit compression strength, f_p^*; the masonry axial compression strength, f_m^*; and the masonry diagonal compression strength, v_m^*. The latter is considered as an indicator of masonry shear strength.

To determine the axial compression and shear design properties, i.e. strengths and stiffnesses, NTC-M favors laboratory tests of masonry prisms under axial compression, and of masonry walls under diagonal compression. In this regard, any design material property, z_m^*, shall be calculated from Eq. 1, where $\bar{z}_m$ and c_z are the mean value and the coefficient of variation, respectively, of the material property under consideration. Just in those cases where laboratory test results are not readily available, such as for single-family dwellings, the recommended strength properties presented in Table 1 can be used.

$$z_m^* = \frac{\bar{z}_m}{1 + 2.5\, c_z} \qquad [1]$$

Table 1 Recommended Design Properties for Axial Compression and Diagonal Compression Strengths, MPa

Type of unit	f_p^*	f_m^*			v_m^* ($\leq 0.25\sqrt{f_m^*}$)	
	---	Mortar I	Mortar II	Mortar III	Mortar I	Mortar II and III
Solid clay brick (handmade)	6	1.5	1.5	1.5	0.35	0.3
Hollow clay brick (industrialized)	10	4	4	3	0.3	0.2
Hollow concrete (semi-industrialized)	6	2	1.5	1.5	0.35	0.25
Solid concrete brick	10	2	1.5	1.5	0.3	0.2

General Requirements for Analysis and Design

Analysis Requirements

NTC-M has been organized according to the type of loading for which the wall had to be analyzed and designed (i.e. vertical, lateral). Therefore, general analysis and design requirements were spread out in different chapters. Aimed at facilitating its use and understanding, requirements for analysis under vertical and lateral loads in NTC-M 2002 were put together in the same chapter. Strength reduction factors, and general design and detailing rules were also included in that chapter.

Previous versions of NTC-M have favored the use of a simplified method of analysis to distribute the earthquake-induced lateral loads among the walls. This method is allowed for symmetric and low-rise buildings. According to NTC-M, buildings are expected to be "quite symmetric" so that the dynamic torsional effects can be neglected. Additionally, the buildings should be squat so that the flexural demands on walls are rather small and that the distribution of the story shear force among them can only be based on the relative elastic shear and flexural rigidities. Typically, this method is valid for structures up to five stories high.

In NTC-M 2002, the method was improved by quantifying the "quite symmetric" requirement. It had been observed in practice that such ambiguous term had led to distinctly different interpretations. The norm now allows this method when the torsional eccentricity at a given interstory (i.e. distance between the story shear force and the interstory center of rotation) does not exceed 0.1 times the width of the building perpendicular to the direction of analysis.

In recent years, most housing buildings do not fully comply with the set of rules required for the application of the simplified method of analysis. Typically, buildings are not symmetric in plan, do not show a uniform distribution of mass or stiffness along the height, and more often, the height surpasses the limit of 13 m. Therefore, specific guidelines for such cases were incorporated.

For seismic design, NTC-M 2002 requires an equivalent static lateral force analysis and/or a modal analysis. In these analyses, both the shear and flexural stiffnesses of the walls shall be taken into account. In load bearing walls, cracked section properties under shear shall always be considered. Under axial force and bending moments, cracked properties shall only be included when net vertical tension strains can be expected in the wall.

Masonry walls are typically perforated by window and door openings, thus forming lintels and parapets around them. Such elements often possess enough stiffness to modify the free-standing wall deformations. Therefore, the restriction on deformations from lintels, slabs and parapets shall be accounted for. In this regard, as an example, NTC-M 2002 provides guidance on the effective width of slabs to be considered in analysis.

To facilitate modeling of masonry walls, the wide-column frame analogy is allowed (Schwaighofer 1969; Bazán 1998). In this method, prismatic walls are modeled as columns located at wall mid-length. In this analogy, wall mechanical properties are assigned to those fictitious columns, and the beam segment within the wall length is considered rigid (Fig. 1).

For a more accurate estimate of building lateral stiffness, the numerical model should incorporate the contribution of transverse walls to the lateral stiffness. NTC-M 2002 also provides guidance on the width of the effective compression flange (Fig. 1).

For walls with a complex array of openings, more sophisticated methods of analysis, such as finite elements, or methods based on stress fields and rules of the theory of plasticity, such as strut-and-tie models, can be used. Most analysis guidelines are applicable in pushover analyses.

As mentioned earlier, infill walls are widely used as partitions in reinforced concrete and steel frame structures. In some instances, infills are built against frame members so that infill wall contributions to the building lateral strength, stiffness, deformation and energy dissipation capacities must be considered. For these cases, NTC-M 2002 allows an infill wall to be modeled as a diagonal strut, with equivalent properties to those of the wall under lateral loads, or as a panel element connected at the frame joints.

Allowable Inelastic Lateral Drifts

Previous versions of NTC-M did not require to check lateral displacements of a load- bearing wall structure under the design earthquake. The MCBC itself, and the technical norms for seismic design, had a confusing requirement, limiting the interstory drift angle in infilled frames to 0.006. In practice, structural designers had often misinterpreted such limit as to be applicable to all masonry wall systems, particularly to load-bearing elements. The lack of explicit limits on lateral deformation can be traced to the simplified method of analysis discussed above; specifically, one assumption of the method is that the total wall stiffness in each direction is large enough so that the lateral displacements are too small to be checked.

In NTC-M 2002, for structures analyzed with methods other than the simplified method, inelastic interstory drifts shall now be checked. Calculated inelastic interstory drift angles are intended to be conservative estimates of story deformations in the inelastic range of behavior. They are calculated through multiplying the drift angles (elastic), obtained in the analysis from a reduced set of lateral forces, by the seismic behavior factor, Q. The seismic behavior factor Q is analogous to factor R_w, used in the International Building Code (2000), and is intended to represent the deformation and energy dissipation capacities of a structural system. Q factors are: 2 for confined masonry walls built with solid units or with multiperforated bricks with horizontal reinforcement and exterior tie-columns; 1 for unreinforced masonry; and 1.5 for other cases.

The allowable inelastic lateral drift angles were derived from experimental results (Fig. 2). Allowable drift angles are consistent with a moderate level of damage, generally accepted in Mexico as a desirable performance of housing under the design earthquake. The allowable inelastic lateral drift angles are the following:

- 0.006 for infill walls;
- 0.0035 for load bearing confined masonry walls built with solid units and reinforced with horizontal reinforcement along the mortar joints or with steel welded wire meshes;
- 0.0025 for load bearing confined masonry walls built with hollow units, with hollow units with horizontal reinforcement, or with hollow units with steel welded wire meshes.

- 0.002 for load bearing internally reinforced masonry walls;
- 0.0015 for load bearing walls in which the specifications for confined masonry and reinforced masonry are not fulfilled (unreinforced masonry).

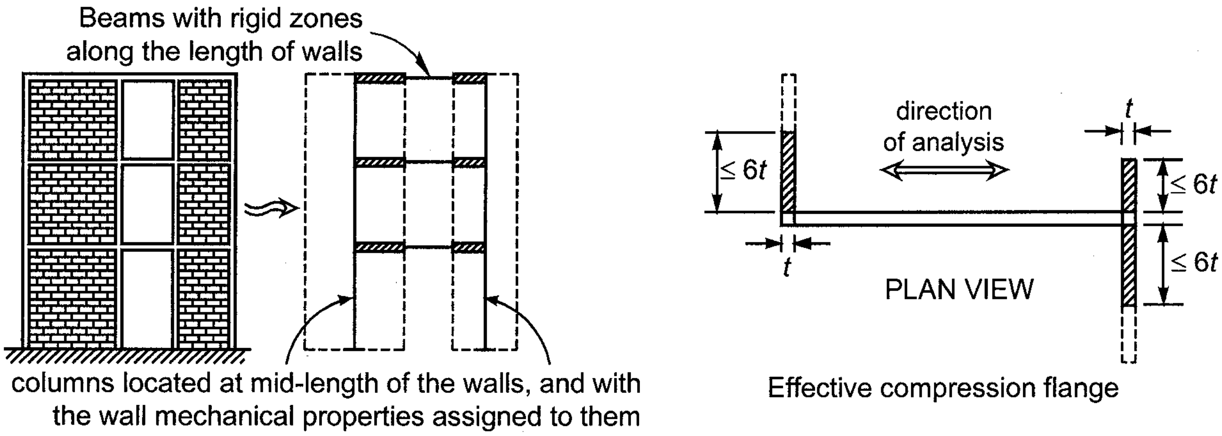


Fig. 1 Analytical Model for Prismatic Walls (Wide-Column Frame Analogy)

Design Guidelines

As mentioned before, general design requirements were grouped in a single chapter. For the first time, specifications for detailing of structural elements were included. These are similar to those in the Building Code Requirements for Masonry Structures (ACI 2002). NTC-M 2002 explicitly indicates that masonry buildings shall be designed for resistance and durability. Consistent with MCBC design philosophy, structures shall comply with strength and serviceability limit state requirements. Regarding design for durability, NTC-M requires, for the first time, that the design and detailing be carried out to achieve a structure's life of 50 years.

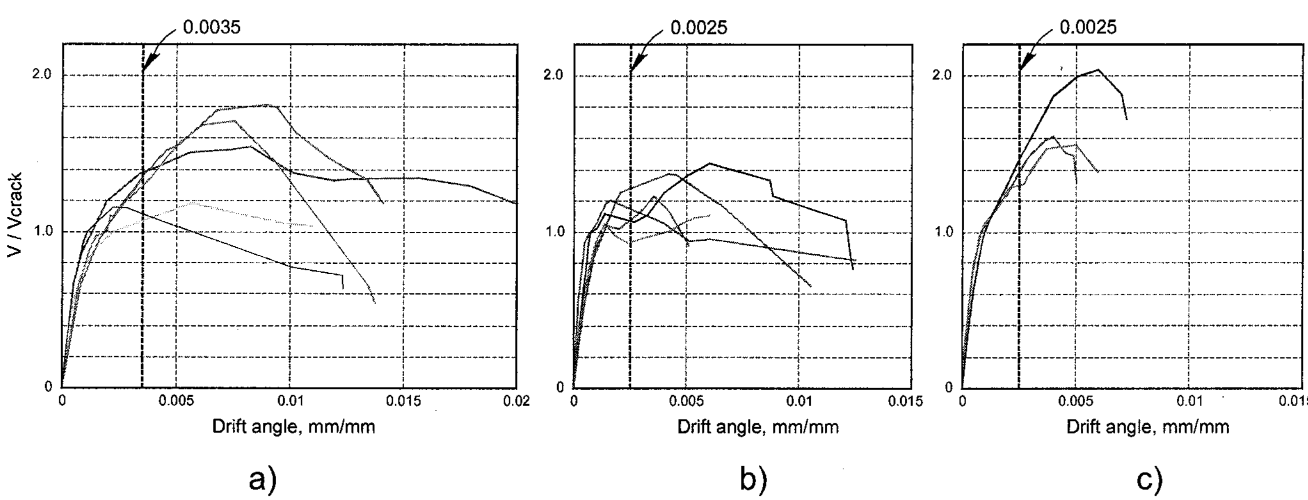


Fig. 2 Allowable Inelastic Lateral Drift Angles: a) Confined Masonry Built with Solid Units and with Horizontal Reinforcement; b) Confined Masonry Built with Solid Units; c) Confined Masonry Built with Hollow Units and with Horizontal Reinforcement

Confined Masonry and Internally Reinforced Masonry

Confined Masonry

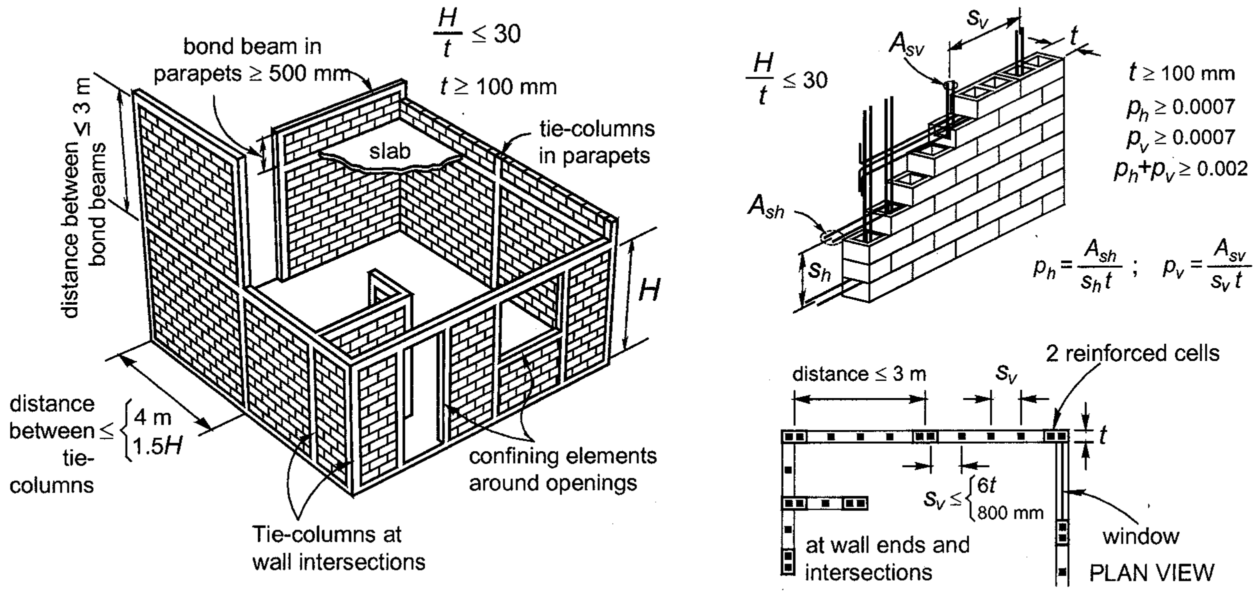
Confined masonry is the most popular masonry construction system in Mexico City and in the country. Developed in Italy at the beginning of the 20^{th} century to improve the seismic performance of masonry structures, it became popular in Mexico City in the 1940's as a method to control wall cracking due to differential settlements that occurred in the soft soil area of the city. Subsequent earthquakes provided evidence of the excellent performance of well-constructed confined masonry structures. Since then, Mexican design and construction professionals adopted the system. As expected from a system that was actually developed on-site, and not through a rational process of testing and research, most design and detailing requirements are empirical.

Confined masonry walls are confined vertically and horizontally with tie-columns and bond beams, respectively. In Mexican buildings, such elements have very small cross-sectional dimensions, typically equal to the wall thickness. Confining elements are intended to tie structural walls and floor/roof systems together, and to improve wall energy dissipation and deformation capacities. When properly designed and detailed, an increase in lateral strength can be quantified.

In NTC-M 2002, efforts were aimed at clarifying and providing a more rational framework for confined masonry requirements. Related specifications were put together into one chapter. To solve code misinterpretations, illustrations, like that in Fig. 3a, were added. NTC-M 2002 requires the ends of tie-columns adjacent to wall openings be reinforced with closely-spaced transverse reinforcement when the design diagonal compression strength of the masonry, v_m^*, exceeds 0.6 MPa. Laboratory tests and field observations have shown that the diagonal cracking of walls made with strong masonry, typically penetrate and shear off the tie-column, in a sudden manner, compromising the stability of the structure under vertical loads.

Internally Reinforced Masonry

Mexican internally reinforced masonry has departed from reinforced masonry systems developed in other countries, such as in the United States, New Zealand and Japan. In these countries, all cells in a hollow masonry unit are typically filled with grout. In contrast, in Mexico, only those with vertical reinforcement are grouted through the wall height; therefore, a large number of cells are left void. Because of the relatively low demand for this system, special units for placement of horizontal and vertical reinforcement are not longer available in the domestic market. Horizontal reinforcement comprises cold-drawn wires which are embedded in the joint mortar. Specified yield stresses of joint reinforcement typically vary from 500 to 600 MPa. Similarly to confined masonry, figures were added to clarify and highlight the requirements (Fig. 3b).



a) Confined Masonry Requirements

b) Internally Reinforced Masonry Requirements

Fig. 3 a) Confined Masonry Requirements; b) Internally Reinforced Masonry Requirements

Wall Shear Strength

A significant improvement in NTC-M 2002 is the explicit calculation of the contribution of horizontal reinforcement to wall shear strength. This new requirement is applicable to both internally reinforced masonry and confined masonry with horizontal reinforcement. In this regard, "horizontal reinforcement" refers to steel wires embedded along the joint mortar and anchored at wall edges or in intermediate tie-columns. It also refers to the horizontal wires of a steel welded wire mesh properly anchored to the masonry and covered with a cement-based mortar. The possible contribution to wall shear strength of prefabricated ladder-shaped reinforcement is explicitly excluded because its mode of failure under cyclic loading is undesirably brittle (Alcocer 1995, 1996a).

A similar approach to that used in shear design of reinforced concrete structures was adopted. The masonry contribution to shear strength is calculated from Eq. 2, in which F_R is the strength reduction factor, A_T is the wall transverse area, and P is the vertical load acting on the wall. This equation is intended to predict the shear force at first diagonal cracking, and was calibrated from experimental results (Aguilar 1996, Alcocer 1996b, 1999).

$$V_{mR} = F_R(0.5\, v_m{}^* A_T + 0.3\, P) \le 1.5\, F_R v_m{}^* A_T \qquad [2]$$

The contribution of the horizontal reinforcement to shear strength is determined from Eq. 3, in which η is an efficiency factor, p_h is the percentage of horizontal reinforcement, and f_{yh} the specified yield stress of the horizontal reinforcement.

$$V_{sR} = F_R \, \eta \, p_h \, f_{yh} \, A_T \qquad [3]$$

The efficiency factor of the horizontal reinforcement when contributing to the wall shear strength, η, was derived from experimental data (Aguilar 1996, Alcocer 1996b, 1999) (Fig. 4). This factor is associated to the extent of horizontal reinforcement that has reached plastic strains at a given interstory drift. In the tests, largest strains in the horizontal reinforcement were recorded near the wall center, whereas at the ends of the diagonal cracks, strains were typically very small (Fig. 4a). The factor η adopted corresponds to that recorded at the allowable inelastic lateral drifts discussed before. The upper limit on the percentage of horizontal reinforcement indicated in Fig. 4, is related to the masonry crushing strength. The lower limit corresponds to the percentage of horizontal steel needed to maintain the strength at first diagonal cracking.

Infill Walls and Unreinforced Masonry in NTC-M 2002

Few changes were introduced for the design of infills. Aimed at precluding a shear failure at the ends of the columns, and following a capacity-design approach, each column is requierd to be designed and detailed to resist a shear force equal to half of the lateral load taken by the infill (Esteva 1966). The wall contribution to lateral strength is calculated from Eq. 4.

$$V_{mR} = F_R \, (0.85 \, v_m{}^* A_T) \qquad [4]$$

In NTC-M 2002, unreinforced masonry structures refers to those that do not comply with all the requirements to be classified either as confined masonry or as internally reinforced masonry structures. Recent earthquakes have provided evidence of the large seismic vulnerability of unreinforced masonry construction in Mexico (Alcocer 2001; López 2001). To discourage the use of unreinforced masonry, reinforcement for structural integrity is now required. This is to be placed vertically at wall intersections and at every 4 m, and horizontally along the top of the walls. The percentage of integrity reinforcement is, roughly, two-thirds that required for confined masonry structures.

Construction Requirements, Inspection and Quality Assurance

NTC-M 2002 aims at improving the construction quality through tougher requirements, and through inspection and quality assurance programs. A comprehensive list of items to be specified in structural drawings, and to be checked in the field is included. Such requirements cover topics ranging from material specifications and mechanical properties, to reinforcement detailing (Fig. 5), building tolerances and approved construction methods.

Structural Evaluation and Rehabilitation of Existing Structures

Requirements for structural evaluation and rehabilitation of existing masonry structures were also included. Although the performance of masonry structures in Mexico City has been acceptable, especially during severe earthquakes, it was decided to deal with these topics because NTC-M is used as model in Mexico. The country has a large inventory of vulnerable masonry structures built under previous codes, some of which have suffered damage in recent seismic events. This decision was also prompted by the vast number of non-engineered buildings in urban areas. Depending on the type of element affected, damage is divided into structural and non-structural. Structural damage of elements is to be classified in one of five levels, depending on its effect on the performance. NTC-M requires that the impact of element damage on structure performance be taken into account.

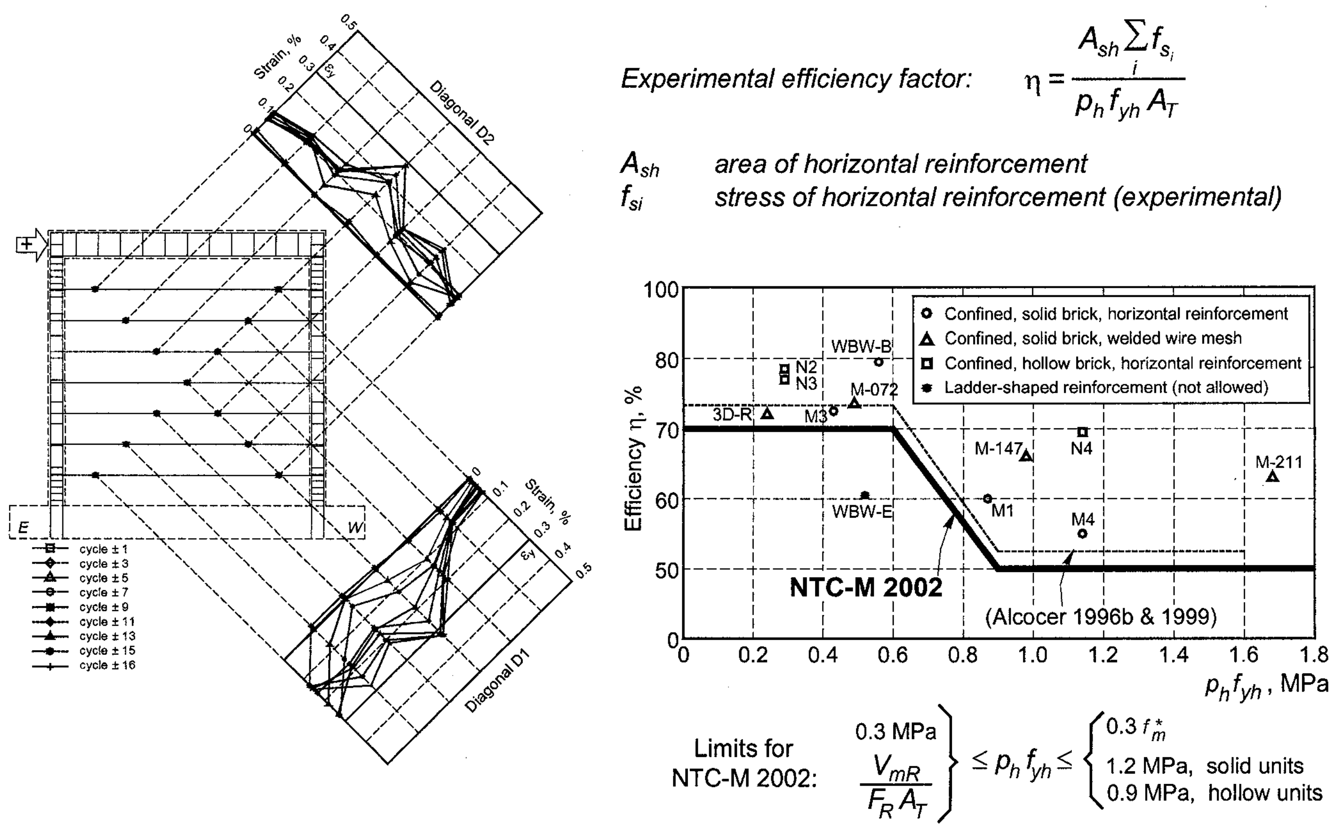


Fig. 4 Efficiency Factor of Horizontal Reinforcement for Contributing to Wall Shear Strength

Experimental Evaluation of Masonry Structures for Seismic Design

In recent years, various masonry systems different from those explicitly considered in NTC-M have been either developed or adapted from other countries, and have been proposed to be used in regions of high seismic hazard. However, there is not a unique criterion for assessing their technical soundness and level of safety, thus raising conflicts and doubts about their use. To overcome this problem, an acceptance criterion was developed based on a similar approach recently published for precast concrete frame structures (ACI 2001). The acceptance criterion is founded on experimental evidence of lateral strength, stiffness decay, energy dissipation capacity and deformability of the walls. NTC-M 2002 clearly defines the experimental protocol to be followed (i.e. loading history, instrumentation, data and damage recording, etc.). Test results from confined masonry walls built with handmade clay bricks were used as benchmark for establishing the criterion.

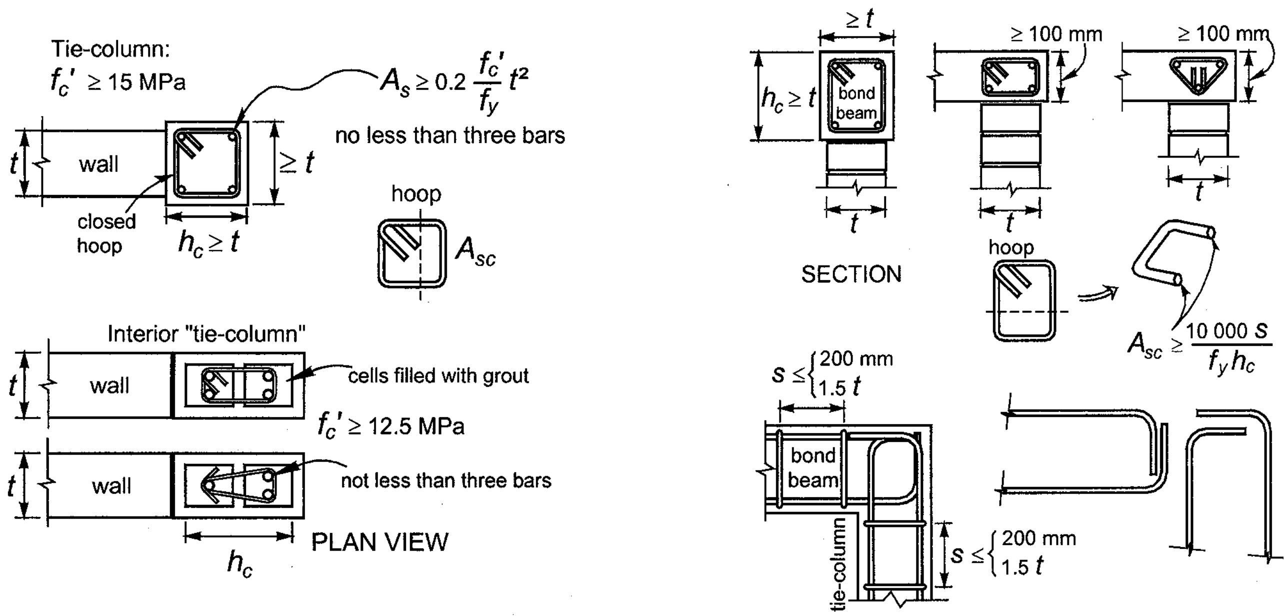


Fig. 5 Detailing Requirements for Tie-Columns and Bond Beams

Concluding Remarks

Most significant modifications to the Mexico City Building Code Requirements for Masonry Structures have been presented. Modifications are largely based on analytical and experimental programs, and field observations conducted in Mexico, particularly those on confined masonry and internally reinforced masonry. Emphasis has been placed on simplification and clarification of requirements, as well as to incorporate the current state of knowledge. An ample number of figures was added. The contribution of horizontal reinforcement and steel welded wire meshes to wall shear strength is now explicit and quantifiable. New requirements for detailing, inspection and quality assurance, and for evaluation and rehabilitation of existing structures are included. A new acceptance criterion for masonry systems subjected to earthquake-induced forces was developed.

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