PRESTRESSED MASONRY: RECOMMENDATIONS TO THE BRAZILIAN CODE

G. A. Parsekian [1], L. S. Franco[2], R. C. Carvalho[3]
[1]Professor, Dept of Civil Engineering, Federal University of Sao Carlos, Brazil, gparsekian@terra.com.br
[2]Professor, Dept of Civil Engineering, University of Sao Paulo, Brazil, luiz.franco@poli.usp.br
[3]Professor, Dept of Civil Engineering, Federal University of Sao Carlos, Brazil, chust@power.ufscar.br

ABSTRACT

Prestressed masonry has been widely used in constructions where the walls are required to resist lateral loads, as in the case of retaining walls, water tanks, one-story buildings and others. Countries where this technology has been used include the United Kingdom, Australia, Switzerland, and United States, where recommendations for design and execution have been a part of local codes and standards for some years. In Brazil only a few cases are known.

In this paper, we present and discuss some recommendations for the design of prestressed masonry for possible inclusion in the Brazilian Code. These recommendations are based on an extensive experimental program conducted with national materials and techniques. Also a review of several international references and codes has been taken into account.

The discussion includes considerations of combined axial compression and flexure and shear design, taking or not taking into account the prestress force in buckling effects, anchorages and bearing stresses, wall stability and prediction of prestress losses due to elastic shortening. Shrinkage, creep, thermal effects, anchorage seating, friction loss and relaxation of prestressing tendon are also considered.

Good practice in execution is also discussed, including the best type of tendon (rod or strand), how to apply prestress (with a torque wrench or hydraulic jack), how to measure prestress force (measuring torque, using direct tension indicators, measuring tendon elongation, measuring the pressure applied to the hydraulic jack), when and where to grout, position of couplers, advantages of applying a provisional prestress in the early days, curing period of final stressing.

KEYWORDS: Prestressed Masonry, Code, Brazilian Code

INTRODUCTION

In the last 30 years, prestressed masonry (PM) has been widely used in many situations, mainly in constructions where the walls are required to resist lateral loads, as in the case of retaining walls, water tanks, one-story buildings and others. Countries where this technology has been used include the United Kingdom, Australia, Switzerland, and United States, where recommendations for design and execution have been part of local codes and standards for some years. According to Biggs [1] "Over 15,000 houses in southwest U.S. rely on prestressing using the Integra system, a concrete block that utilizes a special internal design to decrease heat penetration". New developments including mortarless prestressed wall systems and the use of fiber-reinforced polymer composites are still to come. In Brazil a few examples of PM have been built. Some discussion on these can be found in Parsekian et al. [2].

Most international masonry codes, such as the British BS5628: part 2 – 1995 [3], United States´ ACI 530/TMS 402/ASCE 5-2002 and ACI 530.1/TMS 602/ASCE 6-2002 [4], Australian AS 3700-1998 [5], European Eurocode 6 – ENV 1996-1-1 [6], provide recommendations for prestressed masonry.

The purpose of this paper is to discuss recommendations for the design and execution of prestressed masonry in Brazil and suggest chapters for these topics in the national code. Recommendations to the Brazilian Code are presented throughout. These recommendations are the result of analyses of the international codes and other references and of an extensive experimental program conducted with national materials and techniques detailed in [7].

DESIGN

The following assumptions are made when designing PM:

a) tensile strength of masonry is ignored;
b) plane sections remain plane when considering strain distribution in the masonry compression;
c) the distribution of stress is uniform over the whole compression zone.

Assumptions (b) and (c) are made in every international code reviewed and were verified in laterally loaded prestressed masonry described in [8]. From these test results the linear and uniform stress distribution over a cross section of prestressed masonry until tension occurs was confirmed. Thus stresses can be calculated by classical materials strength elastic theory. After tension appears, there is still the possibility of applying a great deal of load, but the stress distribution starts to be nonlinear from this point. Since prestressed masonry sections are often designed for no tension, there is still a broad "safety reserve" in the design. It is also noteworthy that under tension, prestressed masonry can experience large cracks opening and wall displacements without rupture, which indicates great ductility. In this first recommendation to include prestressed masonry design in the Brazilian code, we should not consider allowing tension in the section, but such considerations can eventually be taken into account in future revisions. Assumption (a) is discussed in the next item.

Prestress Force Design

Prestress force design for the ultimate limit state assumes that no tension should be applied to any section. This assumption is still conservative since usually zero tension is just verified for the serviceability limit state of prestressed concrete structures design. In this case, after calculating the prestress force, the section is verified for the ultimate limit state and some small reinforcement may be needed. This conservative design is suggested here because prestressed masonry in Brazil has just started to be used. Research on design for the ultimate limit state is underway and may lead to more economic designs in the future.

Since the current Brazilian masonry codes do not apply ultimate limit state design, recommendations from the concrete code NBR 6118 may be adopted. Thus the prestress force design should follow:

$$\gamma_g \cdot \sigma_{gk} + \gamma_p \cdot \sigma_{pk} + \gamma_q \cdot (\sigma_{q1k} + \Sigma\, \psi_{0j} \cdot \sigma_{qjk}) \leq 0 \qquad \text{Equation 1}$$

where:

γ_g, γ_p, γ_q = safety factors for gravitational, prestress and variable forces, respectively;
ψ_{0j} = reduction factor for the variable forces combination;
σ_{gk}, σ_{pk}, σ_{q1k}, σ_{qjk} = characteristic stress for gravitational, prestress and major variable force, j others variable forces, respectively

Table 1 shows the safety factors stipulated in the Brazilian concrete code. A prestress loss of 35% may initially be assumed when calculating the prestress force needed. In some situations, the prestress force may be applied with a torque wrench in a rod and nut system, usually when the prestress force is small (less than 100 kN per rod for example). In this case a direct tension indicator (DTI) may be used to certify the force applied, but in some situations the prestress force may be measured indirectly by means of the torque applied. Since the relation between torque and force depends highly on the coefficient of friction between the parts, this relation may have a wide margin of error.

When not using a DTI, we recommend that the required torque is calculated from:

$$T = 0.27 \cdot \phi \cdot F \qquad \text{Equation 2}$$

where :

T = torque in N.m;
ϕ = rod diameter in m;
F = force needed in N.

In equation 2, as a safety precaution, a high friction coefficient between parts has been assumed although some care should be taken in practice to reduce this coefficient, as described later in this paper. The safety factors for the prestress force should then be modified from 0.9 to 0.7 (favorable condition) and from 1.2 to 1.75 (unfavorable condition). If DTIs are used the safety factor should not be modified.

In most cases, the prestress force is determined as follows:

a) When the prestress force is measured precisely and estimating 35% of prestress loss:

$$1.4 \cdot \sigma_{gk} + 0.9 \cdot 0.75 \cdot \sigma_{pk} + 1.4 \cdot (\sigma_{q1k} + \Sigma\, \psi_{0j} \cdot \sigma_{qjk}) \leq 0 \qquad \text{Equation 3}$$

b) When the prestress force is not measured precisely and estimating 35% of prestress loss:

$$1.4 \cdot \sigma_{gk} + 0.7 \cdot 0.75 \cdot \sigma_{pk} + 1.4 \cdot (\sigma_{q1k} + \Sigma\, \psi_{0j} \cdot \sigma_{qjk}) \leq 0 \qquad \text{Equation 4}$$

Table 1 - Safety Factor For Forces (NB6118/2003 [9])

Combination	Gravitational γ_g		Variable γ_q		Prestress γ_p	
	unfavorable	**favorable**	**unfavorable**	**favorable**	**unfavorable**	**favorable**
Normal	1.4	1.0	1.4	1.2	1.2	0.9
During construction	1.3	1.0	1.2	1.0	1.2	0.9
Exceptional	1.2	1.0	1.0	0	1.2	0.9

Finally to calculate the diameter and number of cables, the maximum tension in the cable should be limited to 70% of the characteristic rupture tension for the steel. This limit is slightly less than that prescribed by the Brazilian code but corresponds to the value in all international codes. This smaller limit is probably prescribed in order to reduce steel relaxation.

Masonry Design

The current version of the Brazilian code for concrete masonry structures, NBR 10837/1989 [10], still follows allowable stress design criteria. This code is being revised and will change the design criteria to strength criteria soon. Therefore the latter criteria will be adopted in this paper.

Masonry design should follow:

$$\gamma_g \cdot F_{gk} + \gamma_p \cdot F_{pk} + \gamma_q \cdot (F_{q1k} + \Sigma\, \psi_{0j} \cdot F_{qjk}) \leq R_{m,k} / \gamma_m \qquad \text{Equation 5}$$

where:

γ_g, γ_p, γ_q = safety factors for gravitational, prestress and variable forces, respectively;
ψ_{0j} = reduction factor for the variable forces combination;
F_{gk}, F_{pk}, F_{q1k}, F_{qjk} = characteristic load for gravitational, prestress and greatest variable force, the other variable forces, respectively;
$R_{m,k}$ = masonry characteristic strength;
γ_m = material strength reduction factor.

To determine the material strength reduction factor, several variables should be taken into account, such as the nature of the forces (compression, flexure, tension, flexure and compression, flexure and tension), type of masonry (unreinforced, reinforced, prestressed), factory quality control, and building site control, among others. In the case of Brazil, the definitions of suitable factors are still being widely discussed.

In the Australian, British and European codes it can be observed that, in the worst quality control case, γ_m is stipulated to be 1.33, 2.0 and 2.5, respectively. Thus, until further discussions take place, we recommend adopting $\gamma_m = 2.5$ for prestressed masonry design. This factor may be reduced in the future. When designing masonry before prestress force losses, this factor can be taken as to 2.0, taking into account the provisional character of the load.

Compression

For compression design it is necessary to take into account buckling effects for unbonded tendons:

$$1.4 \cdot \sigma_{gk} + 1.2 \cdot \sigma_{pk} + 1.4 \cdot (\sigma_{q1k} + \Sigma\, \psi_{0j} \cdot \sigma_{qjk}) \leq R \cdot f_{pk} / \gamma_m \qquad \text{Equation 6}$$

$$f_{pk} \leq \gamma_m \cdot [1.4 \cdot \sigma_{gk} + 1.2 \cdot \sigma_{pk} + 1.4 \cdot (\sigma_{q1k} + \Sigma\, \psi_{0j} \cdot \sigma_{qjk})] / R\ ) \qquad \text{Equation 7}$$

If the prestressing cable is laterally restrained by total grouting of block voids or fixing the cable to the masonry at three or more points up the wall, there are no buckling effects of the prestress force. In this case:

$$f_{pk} \leq \gamma_m \cdot \{ [1.4 \cdot \sigma_{gk} + 1.4 \cdot (\sigma_{q1k} + \Sigma\, \psi_{0j} \cdot \sigma_{qjk}) / R] + [1.2 \cdot \sigma_{pk}] \} \qquad \text{Equation 8}$$

where:

- γ_m = material strength reduction factor, equal to 2.0 considering the prestress force before losses and 2.5 for the prestress force after losses;
- R = buckling reduction factor;
- f_{pk} = masonry characteristic compression strength based on the prism test (two blocks and one joint).

Flexure and Compression

When designing prestressed masonry subject to both axial compression and flexure it should be checked that Equation 9 is satisfied. Usually compressive strength due to flexure is 30% greater than compressive strength due to axial load. Since masonry was designed for no tension there is no possibility of flexure and tension.

$$\frac{\text{Compression Due to Axial Load}}{\text{Comp. Strength Due to Axial Load}} + \frac{\text{Compression Due to Flexure Load}}{\text{Comp. Strength Due to Flexure Load}} \leq 1 \qquad \text{Equation 9}$$

Shear

For shear load design it is important to take into account the masonry shear strength improvement due to the pre-compression applied by gravitational and prestress force (after losses), as shown in Equation 10.

$$\tau_d = (\tau_0 + 0.6 \cdot \sigma\ ) / \gamma_m \qquad \text{Equation 10}$$

where:

- τ_d = nominal characteristic shear strength;
- τ_0 = shear strength;
- σ = pre-compression stress due to gravitational and prestress forces.

Bearing Stresses

Under the prestress anchorage the blocks should be grouted or a reinforced concrete end block should be provided. If masonry is grouted bearing stresses should be verified allowing an increase of 30% in masonry strength due to the effect of confined stress. Before prestress losses a further increase of 20% should also be allowed. Thus, the bearing stress of masonry should be limited to:

$1.3 \cdot 1.2 \cdot f_{pk} / \gamma_m$ (before losses),

$1.3 \cdot f_{pk} / \gamma_m$ (after losses). Equation 11

Stresses in concrete should be verified in the case of placement of a reinforced concrete end block. Bearing stresses should be calculated taking into account the anchorage contact area.

Prestress Losses

Prestress losses due to steel relaxation, masonry elastic deformation, shrinkage and creep and thermal movement can be estimated by Equation 12 . Anchor set, friction and steel relaxation losses may be handled as prescribed by the prestressed concrete recommendations.

$$\Delta\sigma = \frac{\alpha_e \cdot \sigma_m}{2} + E_p \cdot [(k_m - k_s) \cdot \Delta T + \varepsilon_{ms} + c \cdot \sigma_m] \qquad \text{Equation 12}$$

where:

- $\Delta\sigma$ = prestress loss;
- α_e = ratio between steel and masonry Young´s moduli (if prestress is applied by only one cable this value should be taken as zero because there is no masonry elastic deformation in this case);
- σ_m = initial prestress at cable center;
- E_p = steel Young´s modulus;
- ΔT = temperature gradient;
- k_m = coefficient of thermal expansion of masonry, equal to $7.2x10^{-6}$ mm/mm/^oC for ceramic masonry and 8.1 mm/mm/^oC for concrete masonry;
- k_s = coefficient of thermal expansion of steel, equal to $11.9x10^{-6}$ mm/mm/^oC;
- ε_{ms} = coefficient of shrinkage for concrete masonry, equal to 0.5mm/m for general case, or 0.6 mm/m if prestress is applied before masonry is 14 days old (for ceramic masonry this value should be taken as zero);
- c = specific creep, equal to 0.5mm/m/MPa for concrete masonry and 0.4mm/m/MPa for ceramic masonry.

MATERIALS AND EQUIPMENT

Cables for prestressed masonry can be either rod or strand. Anchorage and couplers are the same as in prestressed concrete. When using strands it is necessary to apply the prestress force with a hydraulic jack. If rods are used either hydraulic jacks or torque wrenches may be used. Table 2 shows a comparison of prestress force application methods. The advantage of using strands is that high tensile steel can be used and there is the possibility of buying a pre-greased cable with a plastic cover. However there are some difficulties related to coupling and the possibility of significant anchor set losses in this option.

If rod and torque wrenches are used, there is the advantage of ease application of the prestress force since the operation consists basically of turning the nut. Also it is very easy to repeat this operation on the same rod more than once in order to account for some of the losses (e.g. moisture movements). In many cases it can be advantageous to apply only a small portion of the prestress load at an early age and the total load later. This can improve initial stability of the wall and speed up initial shrinkage and creep deformations, which will be compensated for at the final operation. However, there is the disadvantage of not being able to measure the applied force precisely, since the torque/force relation is highly dependent on the friction coefficient between the nut and rod, and between the nut and the anchorage plate. This coefficient depends on whether the parts are rusty or well oiled and clean. Usually about 80% of the applied torque is absorbed by friction. In laboratory tests to measure the torque/force relation during application of prestress force [7], a scatter of 15% was found in results from several operations. This problem may be dealt with in some ways: a direct tension indicator (DTI, Figure 1) may be used to measure the force, the force can be calculated by controlling the numbers of turns and knowing the pitch of the threads, or the margin of error can be allowed for when designing prestress force and masonry strength. Another option is to use a hydraulic jack to apply the prestress force.

Blocks used for prestressed masonry are the same as those used in traditional masonry. The generally available strengths, ranging from 4.5 to 20 MPa (assuming the block gross area as usual in Brazil), are good for most applications.

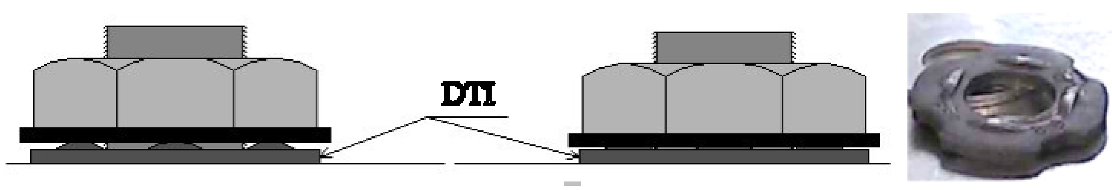

Figure 1 - DTI

Table 2 - Comparison of Methods of Applying Prestress Force

Cable and equipment	Advantages	Disadvantages
Strand and hydraulic jack	- high tensile steel - prestress loss can be smaller (except anchor set) - cable supplied with protective plastic cover and grease - usually less expensive	- coupling not easy - high anchor set loss, which may lead to a need to reapply the force after anchor set - application of prestress force operation not too easy
Rod and torque wrench	- application of prestress force operation is very easy for small loads - is very easy to repeat this operation in the same rod more than once	- poor accuracy when measuring force by the means of torque - DTI not produced in Brazil and needs to be imported - application of prestress force is difficult for great loads (greater than 100 kN per rod)
Rod and hydraulic jack	- provisional load may be applied with a torque wrench	- application of prestress force operation is less simple than with torque wrench

EXECUTION

Usually masonry is built over prestressed cables previously anchored into the foundation. In this case couplers should be specified every two meters. If possible cables inserted into non-grouted voids should be fixed to the masonry at three or more points up the wall.

Care should be taken to cover and protect the cable against corrosion. The most common system is to paint the rod and wrap it with a tape. Another option is to cover the cable with a plastic tube and grease, usually common practice with strands. These recommendations are found in the international references consulted, but are not considered enough in the Brazilian concrete code, NBR 6118 [9], which indicates the need for a protective concrete cover as well.

It is also important to protect couplers, which are usually wrapped with a foil tape lined with bitumen. Anchorages should be embedded into the concrete foundation or covered with concrete. Figure 2 shows a corrosion protection detail.

The prestress force can be applied in a traditional way with hydraulic jacks or torque wrenches when the prestress force is not too great. When using a torque wrench, the following points should be taken into account:

- Use of a Direct Tension Indicator (DTI) is recommended to measure prestress force;
- Hardened washers should always be used between the nut and plate anchorage;
- When using manual wrenches a torque multiplier can also be used;
- To choose the torque wrench a torque range between 0.15 and 0.35 × rod diameter × prestress force, should be chosen;
- The rod, as well as the nut and plate, should be cleaned and greased before prestress application.

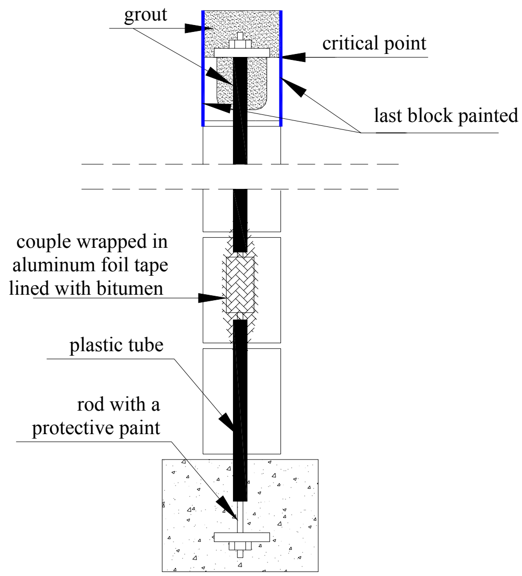

Figure 2 - Details of Corrosion Protection

It is always good to apply a provisional prestress to masonry at an early age in order to improve wall stability and to accelerate creep and shrinkage deformations. These initial deformations will not lead to prestress losses since they will be compensated by the final prestressing. When using rods, provisional prestress can be applied easily with a torque wrench and there is no need for great accuracy to measure the provisional force.

Although there are greater creep and shrinkage prestress losses when applying a prestress force at an early age, the masonry compression strength for hollow blocks at an early age seems to be nearly equal to that at 28 days. Table 3 gives the results from several prism tests of hollow masonry at several ages. It can be seen that at 3 days, the strength is nearly the same as at 28 days. Usually concrete masonry should be stressed at 14 days and ceramic masonry at 7 days minimum. If it is required to apply the prestress force early, the greater creep and shrinkage losses should be taken into account, as related in the previous item. In any case, it is important to confirm masonry strength before prestressing.

Table 3 - Hollow Block Masonry Strength At Several Ages (Ratio To 28 Days Strength) [7]

time (days)	mortar	Ceramic masonry	Concrete Masonry – 6 MPa block strength	Concrete Masonry – 12 MPa block strength
3	43%	95%	104%	95%
7	68%	95%	93%	96%
14	84%	105%	104%	102%
28	100%	100%	100%	100%

SUMMARY

This paper discusses various aspects of prestressed masonry and is intended as a suggestion for possible inclusion in a prestressed masonry chapter in the Brazilian code.

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