Assessment of a type of post-tensioned masonry walls system for dwelling construction in seismic prone areas

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SUMMARY
This work reports the results of an experimental campaign on a type of dry jointed and prestressed masonry. The campaign is part of a larger project with the main objective of to develop an innovative wall construction system for economical dwelling in seismic prone areas of underdeveloped countries. The campaign tested 12 stack bond prisms and 6 regular bond prisms, in order to measure the strength and Young modulus of the material under axial compression and to observe the failure modes. Six wallets, postensioned in the head joints direction were tested in order to determine the diagonal compression strength, the shear modulus, and to observe the failure mode. Under these simple tests, the proposed material behaves adequately; in particular, the shear failure mode presents a very large displacement capacity.

Keywords: Postensioned masonry, Dry joint, Mechanical properties, Experimental test

1. INTRODUCTION

The construction of dwellings is a priority in emergent and underdeveloped countries. Large amounts of housing projects are necessary in order to satisfy the local demand. The construction of these buildings by traditional techniques is, normally, highly uneconomical because both, extensive use of manpower and inefficient use of construction materials. For instance, the main construction system in Mexico, and other Latin-American countries, consists on confined masonry walls with reinforced concrete slabs. The construction of the walls is made purely by hand and with high mortar waste rates. The confining elements are reinforced concrete ones, therefore, their construction includes all the steel, form, concrete pouring and curing works, all made by manpower. On the other hand, highly industrialised techniques, as fully prefabricated structures assembled with large cranes, are not often the best solutions. The reason is that in this type of countries, construction industry is a good opportunity to create jobs for people. Also, in these countries, manpower is relatively cheap. Therefore, intermediate solutions are often preferred, where both, manpower and materials are used efficiently.

There is a continuum search for new and more efficient structural systems. One thread of this research consists on postensioned masonry structural walls. Although, this structural system is still poorly studied, the results show a good seismic behaviour (Rosenboom 2002). Postensioned masonry consists on masonry units placed with mortared or dry joints, and with postensioned steel tendons inside the element, anchored at their ends.

Researchers at the University of Colima, Mexico, have made a proposal of a construction system for dwellings by means of post-tensioned masonry walls and prefabricated reinforced concrete slabs. The material of the masonry pieces is light-weight concrete. Masonry is dry-jointed in order to both, accelerate the construction process and avoid the waste of mortar. Vertical post-tension recovers shear strength to the walls, lost by the absence of mortar joints. Of course, this issue is essential in seismic prone zones because shear strength in walls is necessary to transmit the earthquake effects to the foundation. The proposed system still uses extensive manpower; nevertheless, workers can build walls faster than with mortared masonry. Therefore, construction companies can employ a large number of workers and the efficiency for walls building is high. Also, the proposed system avoids the waste of mortar and the use of reinforcing steel is more efficient than, for instance, in confined masonry.

The aim of the project is to evaluate the mechanical properties of the proposed masonry. Therefore, the paper reports the results of an experimental campaign performed to characterize the compressive and shear behaviour of the dry-jointed masonry. Tests on masonry prisms serve to assess the compressive strength and Young's modulus. Also, tests on masonry wallets serve to assess the diagonal compressive strength and the shear modulus. Additionally, the paper reports results of tests performed on cylinders of the light-weight concrete used to make the masonry pieces, as well as, on the pre-tension steel.

2. STATE OF THE ART

Prestress means the creation of intentional stresses over a structure in order to improve its behaviour under different service conditions. This principle was used for centuries in wooden barrels or chart wheels, for instance. The use of prestress in concrete structures dates from the XIXth Century, almost since the beginning of the history of this structural material. The technology of prestressed concrete was strongly developed by E. Freyssinet from France, since 1928 (Lin and Burns 1981). Postensioned elements are those where the steel tendons are tensioned after the construction of the main element, in contrast to pretensioned elements where the steel is tensioned before the pouring of concrete. In postensioned elements, the tendons can be bonded to the concrete by means of a grout poured into the duct after the tendons tensioning. Nevertheless, unbonded tendons provide more displacement capacity and reduce stress concentrations on steel.

At ancient times, mortar had the function of filling cracks, facilitated the settlement of masonry pieces and smoothed the stresses between pieces. Mortars were made of clay or mud, bitumen, mixtures of mud and straw, burned gypsum, lime or natural pozzolanas, these two last were the precursors of the modern cements. Actually, the most used binding elements are Portland cement and lime, which combined with sand and water provide stronger mortars compared to their ancestors (Drysdale et. al 1994). Dry laid masonry was also extensively used in ancient times, since the stability of those constructions depended basically on their massiveness and not on the mortar strength. Nowadays, most masonry structures include mortared joints, nevertheless, recent research is returning to dry joints as an alternative. For instance, Totoev et. al (2011) have investigated the energy dissipation properties of dry jointed masonry used as infill panels within reinforced concrete frames. The authors argue other advantages of using dry joints as: to avoid the use of mortar at the site, the construction process is simpler, cleaner and shorter, damage does not propagate from one unit to another, and damage is easily repaired.

Light weight concrete is that with a density between 1360 and 1840 kg/m3, and a compressive strength higher than 17.5 MPa at 28 days (Kosmatka et. al 1992). The most common technique for obtaining light weight concrete consists in to include air bubbles into the fresh mixture. The bubbles are obtained by including additives in the mixture. Another alternative is to include very light weight aggregates in the mixture, as pre-expanded pearls (figure 2.1). Pre-expanded pearls are little polystyrene balls of around 2 to 5 mm diameter (Fanosa 2012). They can be produced on different densities according to particular requirements. Also, they represent an easy and cheap way to produce small quantities of light weight concrete, as including air additives are sold only in large volumes.

Figure 2.1. Pre-expanded polystyrene pearls

3. METHODOLOGY

3.1. Masonry pieces elaboration

All the masonry pieces used in this research were produced at the Materials Laboratory of the University of Colima. They were 300 mm long, 150 mm wide and 100 mm high, as shown in figure 3.1. The pieces had a vertical hole of 9.5 mm diameter at ¼ of the length in order the steel tendon passed through. Light weight concrete with pre-expanded polystyrene pearls was used for the masonry pieces production. The Mexican construction code (GDF 2004) specifies a minimum design compressive strength of 10 MPa for concrete masonry pieces. Therefore, seven proposals for concrete mixtures were tested; the main variable between them was the pearls quantity. Three concrete cylinders were poured with each mixture; their dimensions were 100 mm diameter and 200 mm height. Compression tests at 7, 14 and 28 days of these cylinders indicated that only 2 of the 7 mixtures had more than the required 10 MPa strength. The cheapest of these mixtures was selected and all the required pieces were produced. The mixture selected consisted on 1.00 part of Portland cement, 1.00 part of sand, 0.50 parts of water and 0.0045 parts of pre-expanded pearls. This mixture provides a concrete with density 1565 kg/m^3 and f'_c=12.2 MPa.

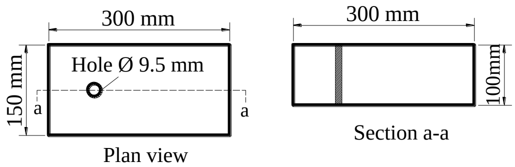

Figure 3.1. Masonry piece dimensions

3.2. Test specimens elaboration

According to the norm ONNCCE (2002a) a masonry prism for compression test has at least 3 pieces and a height to width ratio between 2 and 5. Therefore, masonry prisms of 4 pieces were elaborated of 300x400x150 mm. A set of twelve stack bond prisms was tested and, in order to assess the effect of head joints on the compressive strength, another set of six regular bond prisms was tested, see figure 3.2.

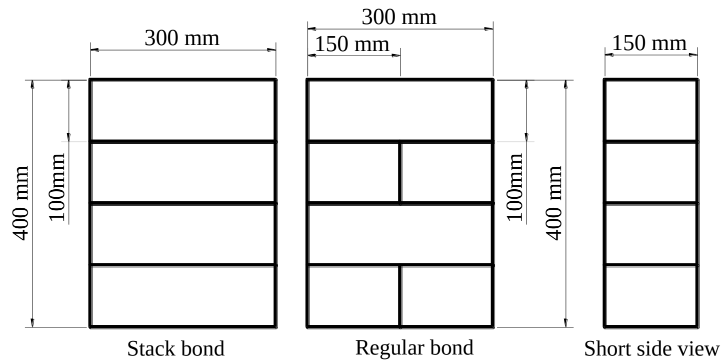

Figure 3.2. Masonry prisms dimensions

A set of six wallets was elaborated according to ONNCCE (2002b). They had four rows and dimensions 450 mm length, 400 mm height and 150 mm width, see figure 3.3. Prestress was applied only in the vertical direction, by means of a 5 mm diameter tendon. The prestressing force applied was 24.6 kN, measured in the jacket just before anchoring the tendon. This force corresponds to a mean compressive stress on the wallet of 0.36 MPa and 1250 MPa on the tendon. Two steel plates served to anchor the tendons, their dimensions were 280x150x38.1 mm.

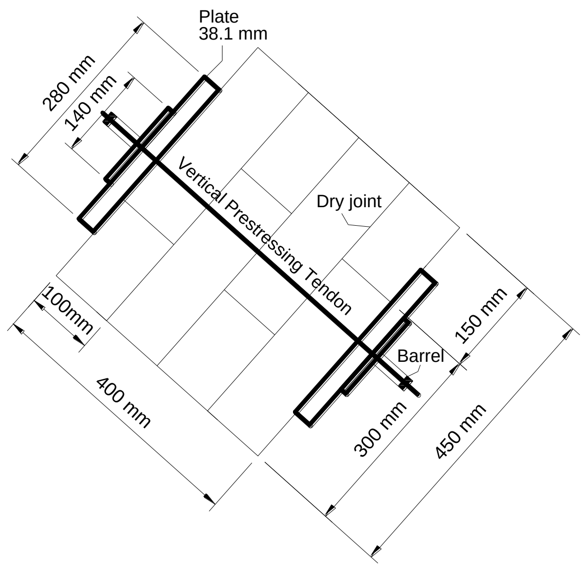

Figure 3.3. Masonry wallet dimensions

In order to know the mechanical properties of the steel tendons, three samples 500 mm long, were tested experimentally under axial tension. The measured properties were Young modulus, maximum stress and yield stress.

3.3. Testing

The tests on prisms and wallets were performed with a universal testing machine with 600 kN capacity, at the School of Civil Engineering of the University of Colima. Digital extensometers, with precision of 0.001 mm measured the displacements between pairs of vertical or horizontal sections of the specimens. Figure 5 presents a masonry prism under testing. The figure shows the frames used in order to fix the extensometers to the prism (another extensometer was placed at the opposite side of the prism). Figure 3.4 also display the sulphur layers poured at the bottom and top faces of the prism in order to smooth the contact surfaces and distribute the force applied through a 320x160x20 mm steel plate. The testing machine applied load to the prisms moving at a rate of 1.25 mm/min. Readings of the extensometers were registered at 10 s intervals during the entire test and the applied load was recovered from the testing machine register. In the case of wallets the rate of the test was 0.5 mm/min.

Figure 3.4. Masonry prism under testing

4. RESULTS

4.1. Masonry prisms

Masonry stack bond prisms had a name as PCL-X, where PCL identified this type of specimens and X was replaced by a number between 1 and 12, identifying each individual prism. Table 4.1 presents the results, strength and Young modulus (E_m), of the masonry stack bond prism tests under axial compression. The strengths reported are affected by a factor that takes into account the prism slenderness according to ONNCCE (2002a). The lower rows of Table 4.1 present the average, standard deviation (St. dev.), coefficient of variation (CV) of both parameters, and, finally, the design strength, f^*_m. This design strength is calculated as a function of the average strength and its coefficient of variation, according to ONNCCE (2002a).

Table 4.1. Results for masonry stack bond prisms

Prism name	Strength (MPa)	E_m (MPa)
PCL-1	10.54	3162
PCL-2	10.33	2622
PCL-3	9.60	2376
PCL-4	9.19	2295
PCL-5	8.47	2167
PCL-6	9.51	2082
PCL-7	10.49	3336
PCL-8	8.60	1758
PCL-9	10.29	2962
PCL-10	5.23	2146
PCL-11	8.61	2341
PCL-12	6.69	1544
Average	9.37	2592
St. dev.	1.59	675
CV	0.17	0.26
f^*_m	6.59	-

The names for the masonry regular bond prisms were PJV-X, where PJV was the identifier for this type of specimens and X took the numbers between 1 and 6, for each of the individual prisms. Table 4.2 shows the results of the axial compression tests on regular bond prisms.

Table 4.2. Results for masonry regular bond prisms

Prism name	Strength (MPa)	E_m (MPa)
PJV-1	5.99	1921

PJV-2	10.06	3789
PJV-3	5.09	1347
PJV-4	5.35	1401
PJV-5	10.75	1463
PJV-6	13.45	2177
Average	8.45	2017
St. dev.	3.46	928
CV	0.41	0.46
f^*_m	4.18	-

Figure 4.1 shows a typical stress-strain curve of a masonry prism (PCL-7). The curve starts with a low stiffness, which quickly increases until a maximum, and then there is a linear part. The stiffness decreases again when damage starts until the maximum stress. At this point, there is a steep decrease in strength, and the curve ends with a plateau at about half the peak stress.

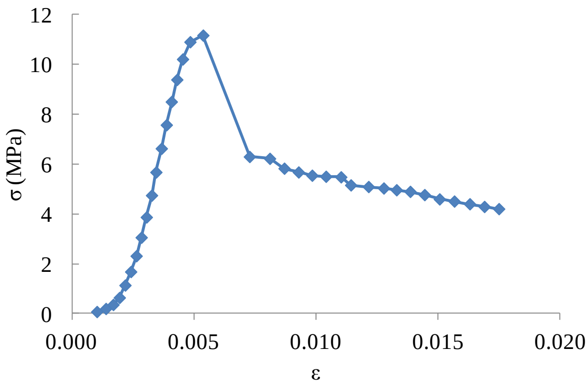

Figure 4.1. Stress-strain curve for PCL-7 prism

4.2. Masonry wallets

Masonry wallets had a name as MP-X, where MP identified this type of specimens and X stands for the consecutive number of each wallet. The wallets MP-1 to MP-4 were used to refine details as the application of prestress or the measurement of strains. Therefore, Table 4.3 presents the results for the 6 wallets tested once those details were fixed. This table includes the diagonal compressive strength and the shear modulus for each specimen. Lower rows have the same meaning as in previous tables and v^*_m is the design strength, obtained according to ONNCCE (2002b).

Table 4.3. Results for masonry wallets

Wallet name	Strength (MPa)	G_m (MPa)
MP-5	0.33	123.8
MP-6	0.52	118.4
MP-7	0.52	55.9
MP-8	0.27	5.6
MP-9	0.24	102.0
MP-10	0.21	89.4
Average	0.35	82.5
St. dev.	0.14	44.8
CV	0.40	0.54
v^*_m	0.18	-

Figure 4.2 presents a typical shear stress-strain curve for a wallet, in this case MP-9. The curve presents an initial linear branch, followed by a very irregular nonlinear behaviour, characterized by several up-ward and down-ward branches around an almost constant value of the shear stress. Nevertheless, an average strain-hardening behaviour is observed in the wallets. This nonlinear behaviour is attributed to sliding on the horizontal joints (figure 4.3) that increases the strain, and is

responsible for the down-ward jumps, without reducing the overall strength. Together with the sliding, cracks appear in the masonry pieces mainly parallel to the vertical joints.

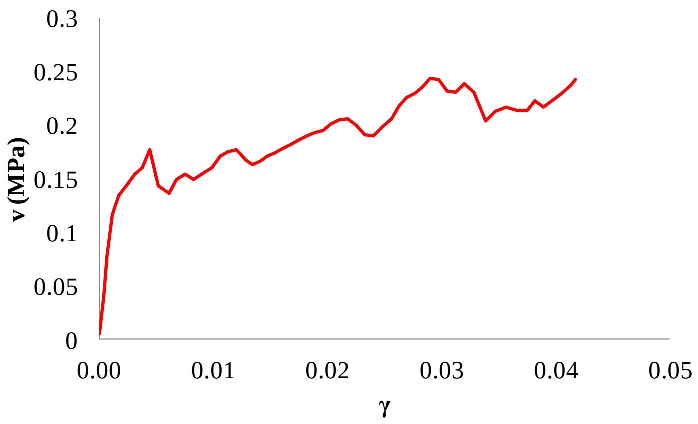

Figure 4.2. Shear stress-strain curve for MP-9 wallet

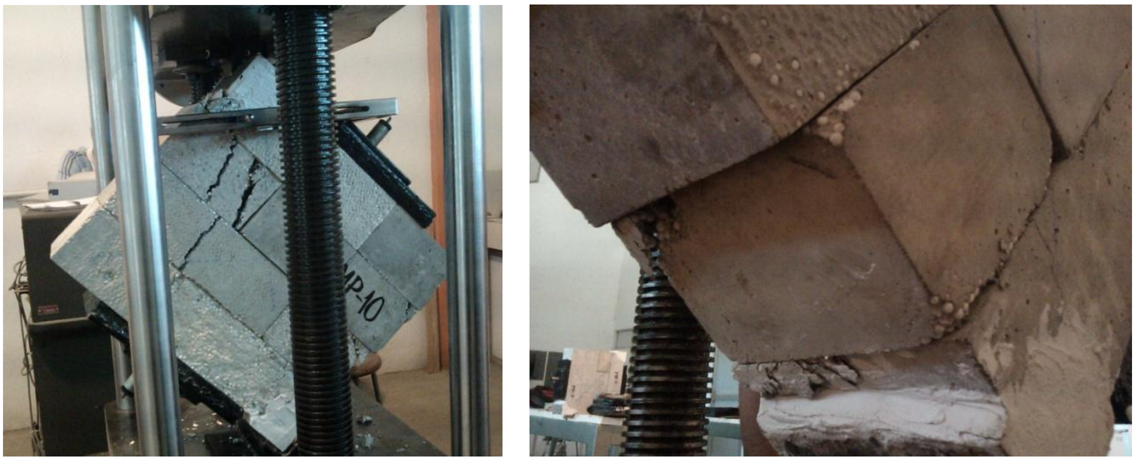

Figure 4.3. Cracking and sliding behaviours in a wallet

5. DISCUSION OF RESULTS

5.1. Masonry prisms

Masonry stack bond prisms present a strength coefficient of variation not so high, according to table 1. The design strength of 6.59 MPa is very high compared to the 1.5 to 2.0 MPa suggested by the Mexican norm (GDF 2004) for light weight masonry, depending on the mortar quality. The coefficient of variation of the Young's modulus is higher, as expected.

The regular bond prisms present a larger strength coefficient of variation and lower design strength (table 2), relative to the stack bond prisms. This behaviour was expected because of the introduction of two irregularities, the vertical joints and the small differences in height between the half pieces in the first and third rows. The design strength reduction, respect to stack bond prisms is 36%. The regular bond prism strength is 4.18 MPa, still very high respect to the design strengths suggested by GDF (2004). Respect to the Young´s modulus of regular bond masonry, the coefficient of variation is higher and the average is lower, compared with stack bond values. The reduction in the Young's modulus amounts 22%.

The steep down-ward jump after the peak in the normal stress-strain curve can be considered as a drawback of the proposed material for the construction of structures in seismic regions. Nevertheless, it must be taken into account that the walls will be confined by the prestressing action. This confinement surely will stabilize the compression failure mode in the proposed system.

5.2. Masonry wallets

Masonry wallets present a strength coefficient of variation relatively high, according to table 3, but comparable with that of the regular bond prisms. The design strength of 0.18 MPa is low compared to the 0.2 to 0.3 MPa suggested by the Mexican norm (GDF 2004) for light weight masonry, depending on the mortar quality. The coefficient of variation of the shear modulus is higher, as expected. The average value of the shear modulus is very low; it represents only 4% of the Young's modulus. This is indeed a drawback of the system as tested by the moment. We are on the way to test another set of wallets with prestress in both, vertical and horizontal directions. We expect that the masonry prestressed in two directions will improve its mechanical properties. Another option is to use a higher prestress level, as the compressive stress on the masonry applied in these tests represents only 9% of the design strength.

6. CONCLUSIONS

This document reports the first results in the development and assessment of a dwelling construction system based on dry joint masonry walls, with postensioned steel tendons and light weight concrete masonry pieces. This preliminary results show a good behaviour of the masonry under axial compressive stresses. Nevertheless, the behaviour under shear stresses is definitively poor. It is expected that postensioning the wallets in two directions or increasing the level of prestress will improve the shear behaviour, in such a way that the system be adequate for buildings in seismic prone areas.

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