SEISMIC PERFORMANCE OF CONFINED MASONRY BUILDINGS WITH TUBULAR BRICKS IN DEVELOPING AREAS

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ABSTRACT :

In many developing countries there are low-income zones in urban areas where people build their houses with non-engineered or even non-structural materials. The main reason for this situation is the low cost of these materials and their workman. Peru is a high earthquake-prone country located in the Circumpacific Seismic Belt. Its capital, Lima City, as well as other important cities of the country, has experienced a fast growth of the urban area around the outskirts. A lot of houses in these areas have been built with tubular-masonry bricks. These bricks were initially launched only for non-structural purposes – uses in partitioning walls or parapets – but were progressively used to build structural walls by non-engineering contractors in non standard buildings, which are the most not only in the outskirts but also in certain consolidated zones of the main town. This reality deserved a study to evaluate the actual seismic vulnerability of these buildings, subjected to possible design ground motions. To reach this goal, a series of tests were carried out in the components (bricks, mortars, and little walls) and in four confined tubular masonry walls, which were submitted to cyclic horizontal loading tests. A comparison of the performance of walls of different materials is shown. Based on inelastic analysis of simplified models of small buildings, interesting differences between the seismic performance of solid masonry buildings and that of tubular masonry buildings were found and discussed. An acceptable seismic performance could be possible to reach in two-story buildings mainly with high wall-density and regular structural configuration. These discussions are finally related to the actual performance of these types of buildings during the Mw 7.9 Pisco, Peru earthquake, occurred in August 15th, 2007.

KEYWORDS: Non-engineered buildings, confined masonry, cyclic tests, seismic performance

1. INTRODUCTION

The massive use of tubular-masonry bricks started in the decade of 1990, with a predominant use in the outskirts of Metropolitan Lima Area. A survey developed by the authors (Salinas and Lázares, 2007) in some Northern districts of Lima City showed an important volume of houses built with tubular-masonry, reaching up to 57% of the total amount of surveyed housing. The majority of these buildings were built by non professional contractors, without professional direction, and therefore many of them have defects in the structural configuration and constructive problems, as it is observed in Figure 1. Two types of tubular bricks were chosen in this study, one of these was typical of standardized fabrication and the other was typical of non standard fabrication; in Figure 2 the storage of bricks – exposed outdoors without safety – in an unconventional factory is shown.

Figure 1. Left: buildings with tubular-masonry bricks.
Right: Storage of tubular-masonry bricks in unconventional factory.

2. PROPERTIES OF THE BRICKS USED IN TESTS

As it was mentioned, two types of bricks were chosen, the first was made with standard process – and was called S – and the second was made with unconventional (non standard) process, called U. The external faces and shape of the bricks are similar, with six horizontal holes and slight grooves (Figure 2). S bricks have a net area of 5330 mm^2 and U bricks have 8780 mm^2 (Table 1). That means a significant difference of 64.7%.

Table 1. Brick dimensions.

Type of brick	Dimensions (mm)	Thickness exterior (mm)	Thickness interior (mm)	Net area (mm2)
S	110x115x228	8	5	5330
U	100x114x231	10	9	8780

Figure 2. Tubular masonry bricks. Non standard (left) and Standard (right).

Standard tests were done, such as compression test in bricks, compression test in piles and diagonal tension test in little walls. Main results are shown in Tables 2 and 3. It was important to note the values of shear strength obtained in diagonal tension tests. These values are higher than those of masonry used in structural walls. This fact can be related to the joint between the mortar and the lateral faces of the bricks, as it is seen in Figure 3, in which little pieces of solid mortar are formed, working as connectors and increasing the shear capacity in the failure plane. In Table 4 a comparison between values of strengths of masonry for structural purposes and those for non-structural purposes is shown, according nominal values set by Masonry Peruvian standard. Although compression strengths of masonry for structural purposes are higher, shear strengths are less than those for tubular masonry, especially for non standard tubular masonry.

Table 2. Results of compression tests in bricks.

Type of brick	Gross area (mm^2)	f'_b average (MPa)	Standard deviation (MPa)
S	26360	4,33	0,77
U	26330	4,04	0,25

Table 3. Results of compression tests in piles and diagonal tension.

Type of brick	f'_m average (MPa)	v'_m average (MPa)
S	2,21	0,67
U	3,32	0,96

Figure 3. Diagonal tension test in little wall. Right: detail of pieces of solid mortar acting as connectors.

Table 4. Nominal strengths of masonry.

Name	f'_b (MPa)	f'_m (MPa)	v'_m (MPa)
King Kong non standard (*)	5,50	3,50	0,51
King Kong standard (*)	14,50	6,50	0,81
U (**)	4,04	3,32	0,96
S (**)	4,33	2,21	0,67

(*): Solid masonry, Peruvian standard NTE-070. (**): This study.

3. CYCLIC TESTS

Tests were done on four confined masonry walls, two of them with in-plane horizontal load and two with orthogonal horizontal load. Two walls were built with S bricks, the other two with U bricks. The steel reinforcement in the concrete confinement elements was the usual in housing construction. Table 5 shows the basic characteristics of the tested walls.

Main results were obtained from the response in terms of lateral displacements and applied loads. The hysteretic and skeleton curves were used to calculate the maximum ductility and the response reduction factor R. The way of failure was similar in both cases of tested walls; diagonal tension by shear caused the decrease of the capacity. In Figure 4 the final condition of each wall is shown. At the ultimate state, the S-masonry wall had considerable cracking, even with partial destruction of some bricks; the wall reached a maximum drift of 1/200 (0,005). At the same state, the U-masonry wall had more uniform cracking without destruction of bricks; this wall reached a maximum drift of 1/166 (0,006); this best performance could be related to the major thickness of U bricks. In both walls the first cracking appeared at a drift of 1/500 (0,002); this limit would imply a limit in the service state for this kind of material.

Table 5. Characteristics of the tested walls.

Type	Length (m)	Height (m)	Thickness (m)
S	2,65	2,37	0,12
U	2,65	2,37	0,11

Figure 4. Final condition of walls. Left: S-masonry. Right: U-masonry.

Hysteretic curves are shown in Figure 5. Each hysteretic cycle is thin, revealing low capacity of energy dissipation for tubular masonry walls. From the skeleton curves shown in Figure 6, the S-masonry wall had a capacity of 15,86 t and a maximum displacement of 11,6mm, with a yield displacement of 1,6mm.; the U-masonry wall had a capacity of 15,27 t and a maximum displacement of 13,4mm, with a yield displacement of 2,2mm. Maximum displacement ductility (μ) was 7,1 for S-masonry wall and 6,0 for U-masonry wall. Furthermore, R factors were calculated following two criteria, the first based on μ and the second regarding the skeleton curves. Calculated values are shown in Table 6. With the second criterion, R factors for ultimate state level were 3,2 and 2,7 for S and U tubular masonry, respectively; for service state level, R factors were 2,4 and 1,9, in the same order. The R factors obtained in this study are different from those considered in Peruvian seismic standards for masonry for structural purposes, in which a factor of 6 is set for ultimate state level. It is necessary to evaluate the effect of over strength in the response reduction factor for tubular masonry walls, in order to establish a more precise comparison with the values obtained in this study (Rodríguez, 2007).

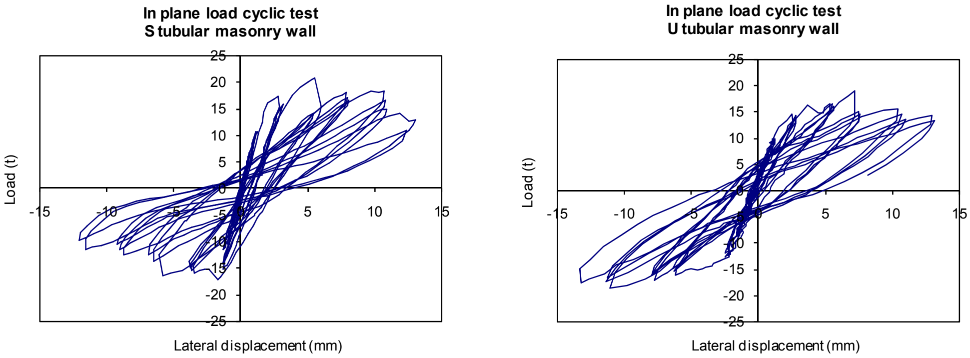

Figure 5. Hysteretic curves. Left: S-masonry. Right: U-masonry.

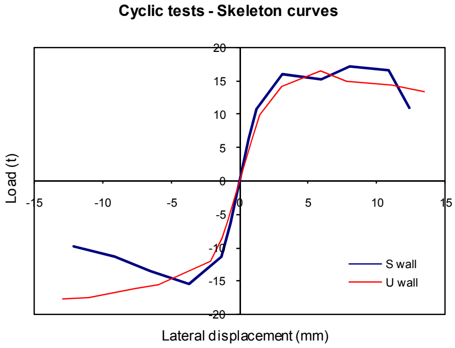

Figure 6. Skeleton curves. In-plane cyclic loads.

Table N°6. Parameters of ductility and R factors.

Type	Maximum ductility (μ)	R (based on μ)	R (service state)	R (ultimate state)
S	7,1	3,6	2,4	3,2
U	6,0	3,3	1,9	2,7

4. ESTIMATED EARTHQUAKE RESISTANT BEHAVIOR

A comparison between the global behavior of solid masonry buildings and that of tubular masonry buildings were done, taking the basic information about tests done in Structural Laboratory of CISMID in past years, compiled by Zavala *et al* (2006). In the Figure 7 the skeleton curves of tubular and solid masonry are shown. In general terms, tubular masonry walls have lesser shear and drift capacity, near 60% to 70% the shear capacity and near 50% the drift capacity of the solid masonry walls. A value of maximum allowable drift for tubular masonry walls were established in 0,0025, according to the values observed in the tests and shown in the Figure 7; Peruvian seismic standards established a limit of 0,005 for solid masonry walls.

In order to compare the global behavior, 2 and 4-story buildings with both types of masonry (solid and tubular) were analyzed, varying the wall-densities from 2% to 6%. Models used in the analysis were 1-DOF models with elastoplastic behavior and equivalent global parameters of mass and stiffness, assuming regular configuration and a predominant first mode of vibration (Zavala *et al*, 2006). Time domain analysis were done in the models, regarding the ground motion record of Lima October 17th, 1966 earthquake, NS component (Figure 8), scaled progressively from 100 gals to 500 gals. In Figure 9 shear base versus lateral drift for 4-story buildings is shown. Cases of wall-density are 4 and 6%. For 4% wall density, maximum lateral drifts are higher than the limit established for tubular masonry, which is 0,0025. For 6% wall density, the behavior has great uncertainty because maximum drifts in U tubular types exceed the allowable drift, while maximum drifts in S tubular types are around the limit. In Figure 10 shear base versus lateral drift for 2-story buildings is shown. Cases of wall-density are 2 and 4%. For 2% wall density, the seismic behavior has great uncertainty because maximum lateral drifts in both types of tubular masonry are around the allowable drift. For 4% wall density, the behavior in both types is relatively safe because maximum drifts do not exceed the allowable drift.

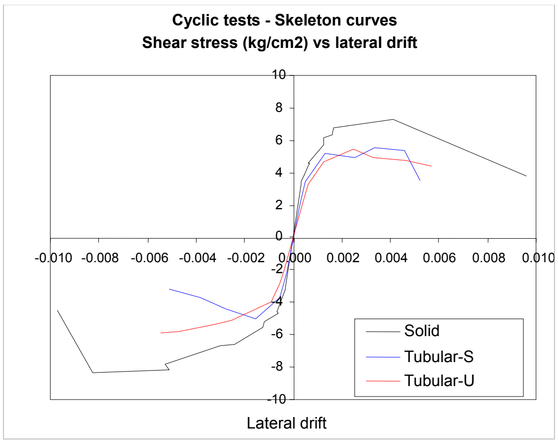

Figure 7. Skeleton curves.
Tubular masonry (this study) and solid masonry (Zavala *et al*, 2006).

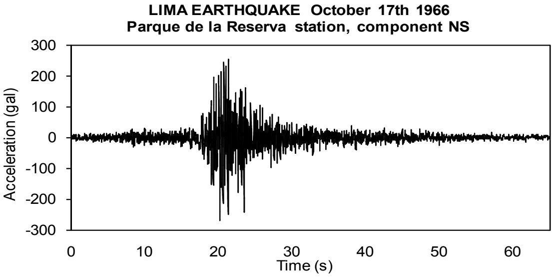

Figure 8. Ground motion record in Lima downtown. October 17th, 1966, Component NS.

In all of analyzed cases, the behavior of the models with solid masonry systems is satisfactory. Although the calculated maximum drift in some cases is higher than that of the tubular masonry system, the allowable drift for solid masonry is not exceeded.

The models of 4-story buildings with tubular masonry systems have an unsafe behavior, because the drift demands are near the allowable drift, even for high values of wall-density; this limit can be exceeded by configuration irregularities or other local effects which are not taken into account in global models. The models of 2-story buildings with low wall-density would also have an uncertain seismic behavior, according the results shown. Besides, there is no noticeable difference in the stiffness in the compared systems, but the major differences are in the shear strength and the calculated drifts in comparison to the allowable drifts.

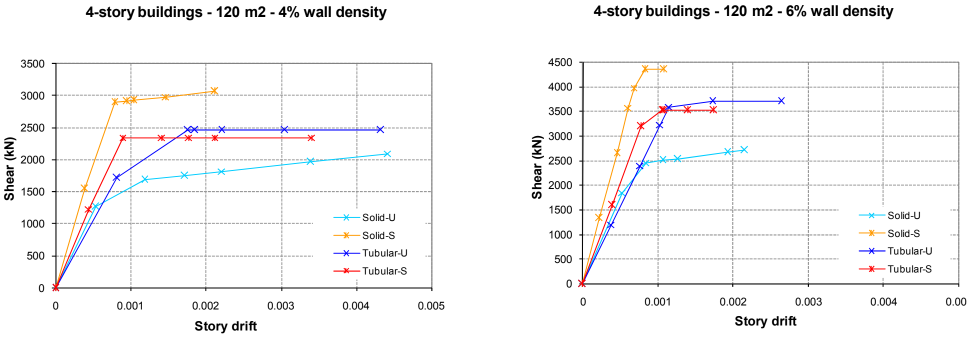

Figure 9. Base shear vs lateral drift. 4-story buildings.

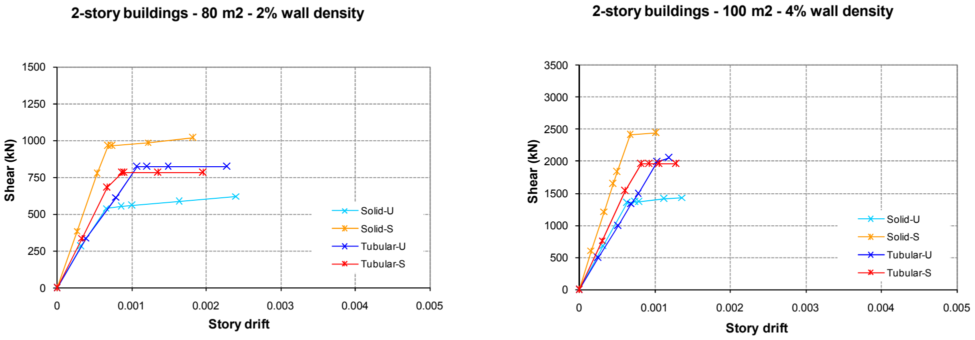

Figure 10. Base shear vs lateral drift. 2-story buildings.

These results belong to a certain time domain analysis. It will be interesting to get similar analysis with other ground motion records, with other characteristics such as long duration, different frequency content (Cornell, 2005), which could lead to major drifts demands.

5. OBSERVED SEISMIC BEHAVIOR OF TUBULAR MASONRY WALL BUILDINGS DURING THE Mw 7.9 PISCO EARTHQUAKE, AUGUST 15th 2007

The Pisco earthquake, August 15th 2007 (epicenter 74km near Pisco city, Mw=7.9) affected central Coast and Highlands of Peru. Reported MMI intensities (IGP, 2007) were VIII in Pisco and Paracas (Ica Region), VII in Chincha and Ica, VI in Callao and Southern Lima. Maximum acceleration recorded in urban areas was 0.34g in Ica, 138 km from the epicenter (CISMID, 2007). There are no ground motion records in Pisco or Paracas, the most affected zone by the earthquake. Figure 11 shows some details of damage in buildings made of reinforced concrete elements and tubular masonry walls. It is important to note the actual source of the collapse or damage, as well as the difference between confined masonry walls and concrete frames filled with masonry. This second type of buildings has the major damage, as well as buildings with irregular configurations, structural or constructive mistakes (short columns, asymmetric arrays, and lack of confinement). Figure 12 shows two buildings made of tubular masonry walls, without damage; both of them have two stories and a regular configuration. When the material is used in buildings regarding its limits, the main sources of vulnerability are the irregularities in the structural or architectural system and the mistakes in the constructive process.

Figure 11. Left and center: damage in buildings with concrete frames filled with tubular bricks
Right: damage in building with tubular masonry walls, lack of confinement.

Figure 12. 2-story tubular masonry wall buildings in Pisco, without damage. Regular configuration.

6. CONCLUDING REMARKS

In Lima and other important cities of Peru, the use of tubular masonry has been extended to the constructions of low-rise buildings, up to 5 stories, basically in the non professional construction sector. For this study two types of tubular masonry, representative of standard and non-standard process, were chosen. In the cyclic tests, the way of failure in the walls was similar; diagonal tension by shear caused the decrease of the capacity. At the ultimate state, the standard tubular-masonry wall had considerable cracking, even with partial destruction of some bricks, reaching a maximum drift of 1/200 (0,005). At the same state, the non standard tubular masonry wall had more uniform cracking without destruction of bricks, reaching a maximum drift of 1/166 (0,006); this best performance could be related to the major thickness of the bricks. Displacement ductility factors and response reduction factors R were calculated. R factors for ultimate state level were 3,2 and 2,7 for standard and unconventional tubular masonry, respectively.

A comparison between the behavior of buildings with tubular masonry wall systems and solid masonry wall systems were done, based on simplified elastoplastic models of 2 and 4 story buildings, assuming different wall densities. Several time domain analyses with a ground motion record, representative of Lima Metropolitan area, showed that 4-story buildings with tubular masonry have a critical seismic behavior, because the maximum drifts are near or exceed the allowable drift for this type of masonry. This limit can be exceeded by configuration irregularities or other local effects which are not taken into account in global models. 2-story buildings with tubular masonry and low wall density have similar situation of uncertain safety.

In the comparison between the tubular and solid masonry systems, the major differences are in the shear strength and the calculated drifts in comparison to the allowable drifts. This fact could limit the possibility of use of tubular masonry only in 2-story buildings with a certain safety. Even for these buildings the configuration should be regular and the wall density should be high, with walls properly confined, in order to get an adequate behavior during a seismic event. Some of these conclusions are in agreement with the observed damage in tubular masonry wall buildings located in the most affected area after the Mw 7.9 Pisco earthquake. However, it is necessary to continue this research in order to define the possibility and conditions of use of this kind of system for buildings in seismic zones.

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REFERENCES

- Alcocer, S. (1997). Seismic behavior of masonry structures: a review. (In spanish) Proceedings of the XI National Congress on Earthquake Engineering. Veracruz, Mexico.
- Cornell, A. (2005). On earthquake record selection for nonlinear dynamic analysis. Proceedings of the Symposium in honor to Dr. Luis Esteva. Mexican Society of Earthquake Engineering, Mexico.
- Kato, H., Goto, T., Mizuno, H., Iiba, M. (1992). Cyclic loading tests of confined masonry wall elements for structural design development of apartment houses in the Third World. Proceedings of the 10th World Conference on Earthquake Engineering. Madrid, España.
- Meli, R., Reyes, A. (1971). Mechanical properties of masonry. (In spanish) Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico.
- Rodríguez, M. (2007). Personal communication.
- Salinas, R. y Lázares, F. (2007). The tubular masonry and its use in buildings on earthquake regions. (In spanish) Proceedings of the International Conference on Earthquake Engineering. CISMID, Faculty of Civil Engineering, National University of Engineering. Lima, Peru.
- San Bartolomé, A. (1994). Masonry constructions – Seismic behavior and structural design. (In spanish) Catholic University of Peru. Lima, Peru.
- SENCICO (2000). Project D/120 report: Experimental study on the net area of clay bricks and its influence in the earthquake resistant behavior of confined masonry walls (in spanish). Prepared by C. Zavala and M. Ramírez. Lima, Peru.
- Zavala, C., Gibu, P. y Salinas, R. (2006). Seismic response diagnosis on masonry housing using experimental models on a screening method. Internal report for Project EDES_B, International Institute of Seismology and Earthquake Engineering (IISEE). Tokyo, Japan.