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EXPERIMENTAL TESTS OF STRENGTHENED SMALL MASONRY WALLS MADE OF HORIZONTALLY-HOLLOW BRICKS ("PANDERETA") IN SEISMIC ZONES

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ABSTRACT

In Peru, more than 50% of the housing buildings are made of confined masonry, but many have several constructive defects. In Lima (more than 10 million inhabitants) this percentage increases to around 80%, and about 75% of these, are non-engineered. The defects include low resistant materials, irregular structures, inadequate locations and soft soil conditions. In the eventuality of an earthquake, many of such structures may suffer severe damage and collapses. Therefore, it is important to study how to improve the structural safety of those masonry buildings, using industrial strengthening with good quality and adequate strength.

This paper shows the experimental tests carried out on small walls, built with horizontally-hollow clay bricks (called "pandereta"), performed at the Pontificia Universidad Católica del Perú. The specimens included masonry without strengthening and masonry with three types of strengthening: welded wire mesh, steel fiber, and basalt fiber, the last two known as Textile Reinforced Mortar (TRM). The "pandereta" bricks should only be used for partition non-structural walls in seismic zones. However, in Peru, frequently, such walls act as bearing walls. The objective of this study is to improve the capacity and ductility behavior, for several types of strengthening that can be applied to the "pandereta" masonry walls. The experimental results show that the small walls strengthened with welded wire mesh or TRM improve the shear strength of masonry. While the strengthening with welded wire increases the thickness of the strengthened walls, the TRM ones do not increase the thickness significantly.

KEYWORDS: *experimental tests, horizontally-hollow bricks, pandereta, seismic strength, textile reinforced mortar, welded mesh*

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INTRODUCTION

Confined masonry dwellings are very popular in Peru and other Latin American countries. In Peru, despite having a standard for earthquake-resistant design and construction with masonry, there are many non-engineered dwellings in which perforated bricks, horizontally-hollow (*tubular* in Spanish, Fig. 1) or hand-made bricks are used, which are not suitable for bearing walls [1]. The Peruvian standard [2] requires the use of solid bricks (with a bedding area of at least 70% of the gross area) for the construction of structural walls. Then, perforated and tubular bricks should be used only for constructing partition non-structural walls. Also, hand-made bricks are only allowed for walls up to two-stories, but due to the lack of control, buildings up to four and five-story are entirely built with hand-made bricks (Fig. 2). A typical constructive error is seen in Fig 2, where tubular bricks are also used in upper floors without confinement elements. In case of an earthquake, those walls are the first to suffer overturning.

Figure 1: Industrial perforated brick and industrial horizontally-hollow brick

Figure 2: Popular informal buildings have walls made of horizontally-hollow bricks

Just in Lima, it is estimated that about 75% of the buildings are informal; this may be indirectly related to the low incomes of the owners. In other words, these structures are built without technical advices and with low quality materials. Hence, they have a high seismic vulnerability [3]. According to Tavera, director of the Peruvian Geophysical Institute, an earthquake of magnitude Mw greater than 8.0 can happen in the future in Lima, and most of the informal dwellings could collapse [4].

One way to reduce the inherent vulnerability is by providing adequate wall density to the dwellings and by strengthening the low-quality masonry walls. Different researchers have been studying the use of reinforcement systems, such as carbon fiber, wire welded mesh, steel reinforced grout, fiber glass, etc. [5][6]; and with very good results in terms of seismic performance. Although there are solutions for seismic strengthening, many owners of non-engineered buildings may not pay for it due to economic reasons. Then, the reinforcement selected should have easy accessibility into the market and have a very competitive cost.

In this paper, two types of strengthening system are studied: steel welded mesh and steel reinforced grout. For that purpose, nine small walls were built and subjected to diagonal compression tests at the Structural Laboratory of the Pontificia Universidad Católica del Perú. The results are promising, since they demonstrate the strength and displacement ductility of all specimens, avoiding also the typical brittle behavior of walls built with tubular units.

SEISMIC STRENGTHENING SYSTEMS

Welded wire mesh

The welded wire mesh consists of deformed bars according to ASTM A496 and ASTM A497. The technical data of the product indicates the size of industrial mesh 2.4x5.0 m, the spacing of wires of 150 mm, 4.5 mm diameter, weight of 1.66 kg/m^2, yield stress of 490 MPa, and ultimate stress of 550 MPa.

TRM

The Textile Reinforced Matrix (TRM) is an effective reinforcement for improving the shear and bending behaviour of non-engineered masonry buildings, with a fast and easy application [7]. It is also considered a non-invasive and reversible material, which is an advantage for strengthening historical structures. The reinforcement is a set of fibers in one or two directions, made of steel or basalt. The mortar used to bond the TRM to the walls is made of lime, and it has a high resistance to fire and also serves for protecting the fibers from the UV rays [8].

The Steel Reinforced Grout (SRG) system is included within the TRM set. These steel fibers are one-directional since they result from twisting two wires around three straight wires (Fig. 3). Perpendicular plastic fiber filaments connect them to form a textile. These fibers are called Ultra High Tensile Strength Steel (UHTSS) with a yield strength of 2800 MPa. Besides, the mortar that acts as a binder is made of lime with type resistance M15 according to EN 998-2 and type R1 according to EN 1504-3 [7].

The SRG has an easy installation on the wall surfaces, which means that it could be directly used by the owners. However, different aspects must be taken into account before the application of the SRG, such as the preparation of the wall surface and to guarantee a good adhesion between textile and mortar. Thus, after treating the surface by removing the dust and moistening it, the first layer of 5 mm thick mortar is applied. Then, the SRG is placed on the fresh mortar and is finished with a second layer of 5 mm thick mortar. Finally, unlike the other types of reinforcement, it is cured for 7 days.

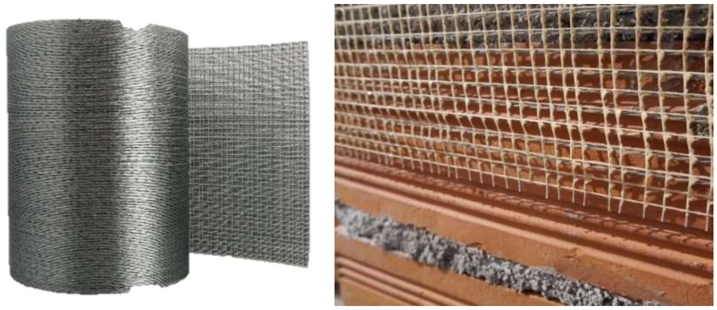


Figure 3: Steel Reinforced Grout (SRG)

CONSTRUCTION OF SPECIMENS

A total of 9 masonry small walls were built at the Structural Laboratory of the PUCP. Three of them to be tested without any strengthening system, 3 with welded mesh and the other 3 with SRG. The small walls were square with a side length of 600 mm. The thickness of the small walls was 110 mm. The mortar's thickness was kept close to 15 mm. Figure 4 shows the construction stage.

The construction of the small walls started by cleaning the dust from the units; and then, wetting the clay bricks to control water's absorption from the mortar. The mortar had a proportion of cement:sand of 1:4. Since the units have horizontal cells, the bricks at two opposite corners were filled with mortar by approximately 200 mm in length. These corners are those in which the compression equipment grips the specimens and applies the diagonal compression load. In previous research, it was observed that those corners need to be solid as possible to avoid local failures (crushing) during the tests.

Twenty-eight days after construction, the application of the strengthening systems was performed.

Figure 4: Construction of small walls

Welded wire mesh

Several points were marked in the mortar joints of three specimens, prior to the reinforcement with the wire mesh. Using these marks, holes were drilled across the specimen, keeping the bricks without damage. A 1.6 mm wire was inserted into each hole with enough length to tie the wire mesh to the wall; then, the crossing wire was bent and fixed to the masonry (Fig. 5). Afterwards, mortar 20 mm thick was used to cover the wall surface including the reinforcing wire mesh. The gross thickness of these reinforced walls was then 140 mm.

Figure 5. Wall specimen strengthened with welded wire mesh

Steel reinforced grout

As in the previous case, the 3 specimens were strengthened after 28 days. The fiber application was following the recommendations given by the manufacturer Kerakoll [8]. Special attention was done to remove all dust from the specimens. The strengthening system consisted of 3 bands of 100 mm height and 1620 mm length for each small wall. The bands are placed around the small wall considering also a 200 mm overlapping. First, the surface where the band is to be placed was wetted. Then, a mortar layer from 3 to 5 mm thickness was placed. The band was placed and pressed, leaving the mortar flow over the apertures of the bands; this is to guarantee a good bond behavior between the masonry and the steel bands. At this step, the band should go around the small wall acting as a hoop. Finally, a second mortar layer was applied, pressing again the mortar to guarantee the bonding. The curing of the mortar was done (twice a day, by wetting) during the first 7 days after strengthening. The 3 bands were placed along with the height of the small walls and equally separated (Fig. 6).

Figure 6: Small wall specimen reinforced with SRG

EXPERIMENTAL TESTS ON SMALL WALLS

All the wall specimens were carefully moved from the construction yard to the laboratory. At the corners, where the small walls were fixed to the loading equipment, a layer of gypsum was applied to level the corner’s surfaces. This was needed to have a better load distribution from the equipment to each specimen and to avoid local failure as much as possible. Also, two Linear Variable Displacement Transducers (LVDT) were placed in each small wall, along the wall's diagonals. The length of each LVDT was 400 mm. Both LVDT served to measure the deformation in each specimen and to compute the shear modulus (Fig. 7).

Figure 7: Test setup of the diagonal compression tests

The diagonal compression load was applied with a hydraulic jack of 200 kN capacity, and with a 10 kN/min as velocity. Special attention was taken at the beginning of the load, giving time to the equipment heads to adapt to the load conditions. The LVDTs were removed (around at 100 kN load) before each specimen failed to avoid any damage to them. The scope of the tests was to record the elastic behavior, and as much as possible, the inelastic stage with the LVDTs. But when those were removed, the vertical displacement at one diagonal continued to be measured by the instrument at the equipment head. Each test lasted about 15 min.

Small walls without strengthening

All the failures were sudden and brittle. Specimens M-1 and M-3 had a failure that started at the corners, where the hollows were filled with mortar to avoid local failure, and continued through the tubular bricks. The failure in M-3 started at the corners and broke the specimen almost with a vertical line. This last failure is an indication of good bonding between mortar and bricks, and most desirable for shear tests (Fig. 8).

a)  b)  c) 

Figure 8: Test of small walls without strengthening, a) M1; b) M2; c) M3

Small masonry walls strengthened with welded wire mesh

These specimens were labelled as M-1-E, M-2-E and M-3-E. All three showed a slow and progressive failure. Wall M-1-E had a premature diagonal failure in the mortar cover, the wire mesh bent and pushed away from the covering mortar. The crack did not go over all the masonry units, only in the cover (Fig. 9 a). Wall M-2-E had a sort of diagonal crack, it could be observed that the wire mesh entered into the plastic range of behavior, due to permanent deformation. The bricks crushed along the cracking (Fig 9 b). Wall M-3-E showed a diagonal crack, also it could be observed that the wire mesh bent and pushed away from the covering mortar (Fig. 9 c).

a) 

b) 

c) 

Figure 9: Failure of walls with wire mesh, a) M-1-E; b) M-2-E; and c) M-3-E

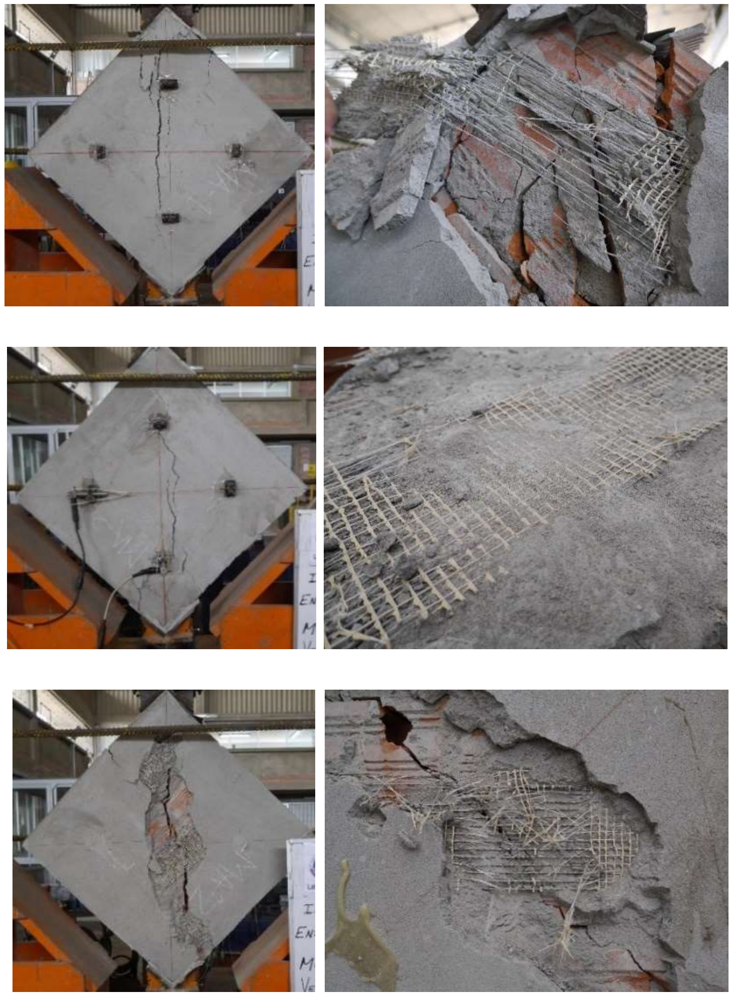
Small masonry walls strengthened with SRG

In all cases, the failure process was slow and with a smeared cracking distribution (M-1-SRG, M-2-SRG, M-3-SRG). The steel fiber bands kept together the wall pieces formed during the test. The bands worked in tension. When the stucco was removed, some parts of the bands showed evidence of elongation. Due to the mechanical process for removing the stucco, some polymer threads -that kept together with the fibers- were cut. There were not bonding failures. In M-2-SRG and M-3-SRG, the crushing of the central unit bricks was observed, but the bands kept them together.

RESULTS COMPARISON

Small masonry walls without strengthening

As seen previously, these specimens were the most fragile and had an explosive failure. Table 1 shows the results of the three walls without strengthening. Wall M-1 has a higher load value than M-2 and M-3.



a)

b)

c)

Figure 10: Failure of walls with SRG, a) M-1-SRG; b) M-2-SRG; and c) M-3-SRG

This specimen had a brittle failure in which the main crack surrounded the entire zone that was filled with mortar at the loaded border. In contrast, M-3 had the lowest strength and had a brittle and sudden failure. The shear strength, v_m, was computed as the vertical force divided by the sectional diagonal area. The characteristic shear resistance v'_m value, was obtained as the average minus one standard deviation. In this way, the set of three walls gave a unit shear resistance of v'_m = 0.9 MPa, however without considering the lowest v_m of M-3, the shear resistance was computed as v'_m = 1.18 MPa.

The shear modulus G for each wall was also computed. It is important to mention that the LVDTs were removed at approximately 60% of the maximum load to avoid damage to them. Then, the elastic interval used from the LVDTs was the one between 20% and 40% of the measured values in force and deformation. Each LVDT length was 400 mm. A summary of the computed values is shown in Table 2.

Table 1: Calculation of v'_m for small walls without strengthening

Specimen	Dimension (mm)				Diagonal area (mm^2)	Max load (kN)	v_m (MPa)
	Side 1	Side 2	Thickness	Diagonal			
M-1	605	620	132	866	114 348	148.30	1.30
M-2	605	615	135	863	116 464	136.30	1.20
M-3	608	622	136	870	118 292	100.80	0.85*
						Average=	1.25
						Standard deviation=	0.07
						v'_m=	1.18

* M-3 was not considered for computing v'_m due to is low value and type of failure

Table 2: Calculation of G for small walls without strengthening

Specimen	LVDT (mm)	Diagonal Area (mm^2)	ΔP (kN)	ΔD vertical (mm)	ΔD horizontal (mm)	$G=\Delta\tau/\Delta\gamma$ (MPa)
M-1	400	114 348	29.60	0.0464	0.0183	1603
M-2	400	116 464	27.20	0.0417	0.0112	1768
M-3	400	118 292	20.00	0.0472	0.0128	1127
					Average G=	1500

* M-3 was not considered for computing G due to the low value obtained and type of failure

Small masonry walls strengthened with welded wire mesh

The wire mesh reinforcement produced a slow and progressive failure in these three strengthened walls. Wall M-1-E had an unexpected failure, the LVDT had to be retired after the first crack appeared. However, the other two walls had similar failures between them, with similar shear resistance. The wire mesh reinforcement was able to improve the structural behavior of all these walls. Table 3 shows the results of the shear resistance obtained in this case.

Table 3: Calculation of v'_m for walls strengthened with wire mesh

Specimen	Dimension (mm)				Diagonal area (mm^2)	Max load (kN)	v_m (MPa)
	Side 1	Side 2	Thickness	Diagonal			
M-1-E	603	620	138	865	119353	96.8	0.83
M-2-E	605	623	143	868	124184	137.4	1.11
M-3-E	597	615	140	857	119995	137.3	1.15
						v'_m=	0.86

Surprisingly, the unit shear resistance for the walls strengthened with wire meshes was 0.86 MPa, a bit lower than the value for the walls without strengthening which reached 0.9 MPa. The calculation for the shear modulus of these strengthened walls was similar as before, reaching a value of G (M-E) = 1422 MPa, quite similar to the value obtained without any strengthening. It can be concluded that the use of the wire mesh for strengthening gives similar numerical values as without strengthening. However, it does improve the mode of failure, as well as the global wall resistance due to the increased thickness of 140 mm instead of 110 mm.

Small walls strengthened with SRG

In this case, the shear strength of the strengthened small walls increased by 13% concerning the ones without any strengthened system. This value may be considered, for engineering purposes, the same as the ones computed in Table 1. The most important effect of the SRG was to avoid a brittle failure of the small walls. The steel fiber bands allowed the specimens to behave in a ductile manner and to have a diagonal cracking along the loading direction, avoiding local failures at the corners. Table 4 shows the shear strength v'$_m$ of this set of specimens.

Table 4: Calculation of v'$_m$ for walls strengthened with SRG

Specimen	Dimension (mm)				Diagonal area (mm^2)	Max load (kN)	v_m (MPa)
	Side 1	Side 2	Thickness	Diagonal			
M-1-SRG	612	621	140	872	122 355	166.7	1.40
M-2-SRG	622	619	139	878	121 976	161.9	1.35
M-3-SRG	602	624	140	867	121 387	162.3	1.35
						v'$_m$=	1.34

To evaluate the relative displacement ductility among all the small walls, the plots of vertical force vs global vertical displacements (head machine) were analyzed. These records are related to the vertical displacement of the head of the hydraulic jack. It is known that to compute the displacement ductility, all data in the LVDTs should be recorded, but these were removed from the small walls around 70% of the maximum load. Then, a solution to obtain the ductility of each specimen was to measure the displacement capacity of each specimen after reaching its maximum load capacity, and comparing to the end of the elastic range.

In Fig. 11 a comparison of all Force vs Global Displacements is shown. Here it was marked the point of maximum load and maximum displacement of each curve. To infer in a ductility value, just the inelastic displacements were analyzed and written in Table 5. It is observed that small walls without strengthening had a brittle behavior and with almost no displacement ductility. This displacement ratio is given as unity in Table 5.

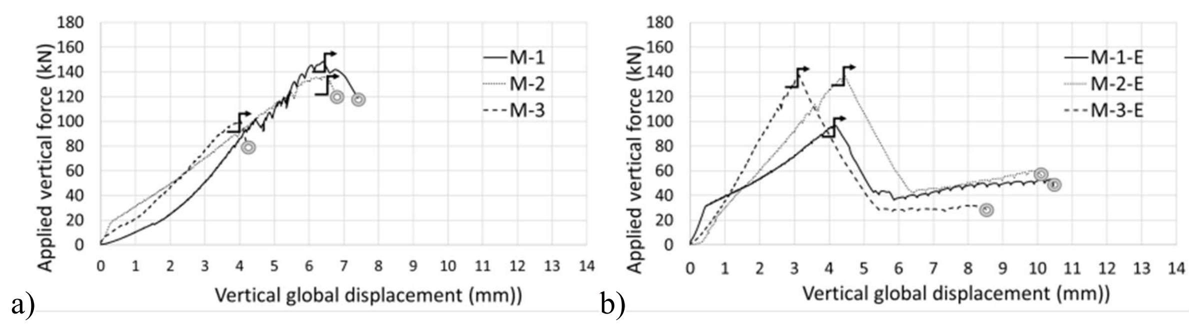
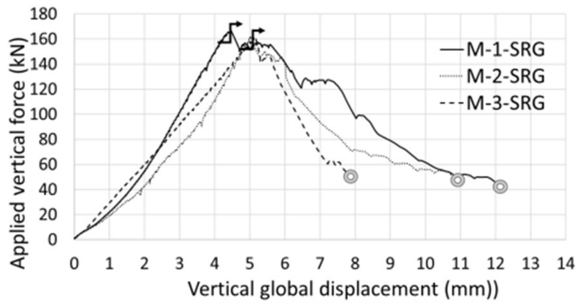


Figure 11: Vertical force vs Global vertical displacement plots, a) small walls without strengthening; b) strengthened with welded mesh and c) with SRG



c)

Figure 11: (continuation): Vertical force vs Global vertical displacement plots, a) small walls without strengthening; b) strengthened with welded mesh and c) with SRG

The small walls with steel welded mesh had a greater load capacity but at failure the units broke, the load decreased to around 30% of the maximum load, and then the strengthening worked and transferred ductility to the small walls. The ductility ratio was 8.4 times more than the previous small walls. The last group of strengthened small walls seemed to have better behavior. The steel bands were perfectly bonded to the masonry units, and allowed a smooth decrease in the capacity and with more energy dissipation. Also, the displacement ductility ratio was around 7.80.

Table 5: Calculation of displacement ductility ratios

Displacement	Average values (mm)		
	M-(1-2)	M-(1-2-3)-E	M-(1-2-3)-SRG
Max	6.40	3.90	4.87
Ultimate	7.10	9.70	10.26
Displacement	0.69	5.80	5.39
Ductility ratio	1.00	8.40	7.81

CONCLUSIONS

This paper showed by shear tests, the lack of displacement ductility of small walls built with horizontally-hollow units. Their seismic capacity should be improved by strengthening; two techniques were studied in this project: the welded wire mesh and the Steel Reinforcement Grout (SRG). Both materials improved the ductility, but the SRG controlled better the cracking distribution inside the walls, allowing better energy dissipation. Also, the SRG had a better bonding with the masonry. Both systems add ductility to the structures.

REFERENCES

[1] San Bartolomé, A., Quiun, D., Araoz, T. and Velezmoro, J. (2013). "Seismic reinforcement of existing walls made of horizontally-hollow bricks" *Proc., 12th Canadian Masonry Symposium*, Vancouver, BC, Canada.

[2] SENCICO. (2006). "Peruvian Masonry Code E.070 (Norma E.070 Albañilería in Spanish)", Lima, Perú.

[3] Lovon H., Tarque N., Silva V. and Yepez-Estrada C. (2018). Development of Fragility Curves for Confined Masonry Buildings in Lima, Peru. Earthquake Spectra. Volume 34(3), 1339-1361.

[4] Andina. (2016). Interview to Dr. Hernando Tavera. https://www.andina.pe/agencia/noticia-igp-hay-alta-probabilidad-un-sismo-magnitud-85-lima-763597.aspx Available at April 2021.

[5] Quiun, D. and Mamani, P. (2017). "Cyclic Load Behavior of Confined Masonry Walls of Horizontally-Hollow Bricks Retrofitted with Wire Meshes" *Proc. 17th World Conference on Earthquake Engineering*, Santiago, Chile.

[6] Tarque, N., Salsavilca, J., Yacila, J. and Camata, G. (2019). "Multi-criteria analysis of five reinforcement options for Peruvian confined masonry walls". *Earthquakes and Structures. Volume 17(2), 205-219.*

[7] Yacila, J., Salsavilca, J., Tarque, N. and Camata, G. (2019). "Experimental assessment of confined masonry walls retrofitted with SRG under lateral cyclic loads". *Engineering Structures. Volume 199, 15 November 2019, Article number 109555.*

[8] KERAKOLL. (2018). Directrices para la consolidación, refuerzo estructural y seguridad sísmica con nuevas tecnologías green (In Spanish).