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EXPERIMENTAL STUDY ON MASONRY WALLS STRENGTHENED WITH STEEL AND PLASTIC STRAPS

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SUMMARY

Ten different techniques for rehabilitation and strengthening of clay masonry walls were investigated using as principal elements steel and plastic straps. The experimental program including specimens with and without previous damage, was divided in three stages: (1) Two prismatic specimens for each technique were tested in diagonal compression (2) Additional tests were performed on prismatic specimens representing the best techniques (3) Four models of masonry walls were tested under reversing cyclic loads. Two walls with previous damage were tested to study the repair method and two walls in this original state for the strengthening method. The experimental results are presented in terms of the hysteretic behavior observed. The increment in strength deformation capacity and energy dissipation is evaluated and compared with other studies related with different repair techniques. Design criteria are proposed from the analysis of the test results. It is concluded that the techniques here introduced and investigated have potentiality to decrease the vulnerability of low cost housing.

INTRODUCTION

In Mexico as well as other Latin-American countries, masonry walls are the main structural components in housing construction. The importance of this system is related to its extensive use in the construction of low cost housing and apartment blocks as well as different kind of buildings such as schools, clinics and community centers. In Latin-America about 90% of the buildings are self-constructed without structural plans Salas [1]. Most of the housing of the rural areas and deprived zones of the cities are made with unreinforced masonry. The seismic vulnerability of this type of construction is very high. Defining seismic risk as the probability of occurrence multiplied by the consequences (losses), many zones in Mexico and others countries are considered of high seismic risk due to the vulnerability of the constructions; this is the case even in zones with moderate seismic intensity, Iglesias [2], Sordo [3]. It is clear that the improvement of the buildings will decrease the risk. Masonry structures are prone to damage during earthquakes because of its high stiffness in relation with its relative low strength. Inclined cracks due to diagonal tension form the principal damage in masonry walls due to earthquakes. Thus it is necessary to investigate repair methods, in this case the objective is to recover the original strength of the masonry. Since vulnerable structures exist in seismic regions, it is necessary to investigate strengthening

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methods., the objective is to increase the strength of the masonry so damage is prevented. Methods for repair and strengthening masonry walls had been studied in Mexico, De la Torre [4] as well as other countries, for instance, Ehsani [5]; Klingner[6]; Schuller [7]. However, most of the techniques involved are expensive because of the materials used and/or because of the qualified workmanship required. In this study new techniques for low cost housing are developed for the repair and strengthening of masonry walls made of burned clay bricks.

The objective of this work is to study methods for the repair and the strengthening of burned clay brick masonry walls using low cost materials and techniques such as steel and plastic straps applied with simple tools.This work was divided in three stages:

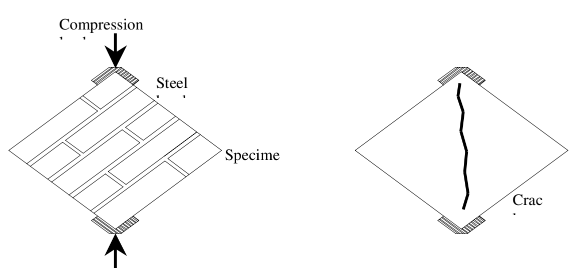
I Ten methods or techniques were identified to be used in cases of repair (walls with previous damage) and cases of strengthening (walls without previous damage). Two prismatic specimens for each method and case were tested in diagonal compression. The analysis of the test results of this exploratory stage permitted the selection of the three best methods.

II Additional tests were performed on prismatic specimens representing the best methods detected in the previous stage. Nine specimens were tested for each method and case. This permitted us to estimate the implicit variability.

III. The analysis of the test results of the previous stages permitted the selection of the best method for repair and the best method for strengthening to be applied in wall models at natural scale. Four wall models were tested under reversing cyclic loads to increasing lateral deformations. Two of the walls were tested first in its original state to induce damage, then the repair technique was applied and tested again.

MATERIALS

The prismatic specimens and the wall models were constructed with burned clay bricks of common use jointed with type II mortar according with local construction practice [Federal 1993]. The average compressive strength of five units was 3.53 MPa. The minimum, according with local code, is 2.45 MPa. Mortar was made of one part of Portland cement, half a part of cement mortar (pozzolanic cement with additions of lime and minerals which is of common use for masonry works in Mexico) and four and a half parts of sand. Six 50mm cubic specimens of mortar were tested with an average compressive stress of 16.48 MPa (minimum 14.13 MPa, maximum 18.84 MPa). For the second stage of the experimental program the average compressive stress of the mortar was 19.4MPa. The specimens used in the experimental program were approximately square in shape. Burned clay units 60,120,270 mm from the same supplier were used to construct the specimens with one and a half units to form the base and five layers to form the height; specimen dimensions of 360 by 360 mm approximately. The specimens were tested in diagonal compression as is schematically represented in Fig. 1.



a)Application of load b) Typical form of failure

Fig. 1: Test of masonry specimens in diagonal compression

EXPERIMENTAL RESULTS

Ten methods were identified using steel and plastic straps as main components. The variables considered were the type of strap, the way the straps were tighten and the devices used to attach the straps to the wall. A short description of each method studied is as follows:

TR1

Horizontal steel straps (32 by 0.50mm) are placed around the wall and fixed with 50mm steel nails or concrete. Extra adhesion is attained with strips of fiber glass saturated with resin underneath of the steel straps.

TR2

Horizontal plastic straps (16 by 0.8mm) are placed around the wall which are tighten with a hand tool and fixed with two double dead-end clamps. Extra adhesion is attained with strips of fiber glass saturated with resin underneath of the plastic straps.

TR3

Horizontal steel straps (32 by 0.50mm) are placed around the wall and fixed at the ends with four 50mm steel nails for concrete.

TR4

Horizontal plastic straps (16 by 0.8mm) are placed around the wall which are tighten with a hand tool and fixed with two double dead-end clamps. Vertical plastic straps with 60mm spacing are added in the same way. A second strap layer is placed on the first.

TR5

In each corner of the wall steel angles with welded steel rings (chain links) are attached and diagonal plastic straps are passed through the links in both sides of the wall. The straps are tighten with a hand tool and then fixed with two double dead-end clamps.

TR6

Horizontal plastic straps (16 by 0.8mm) are placed around the wall and fixed as in TR2. With the aid of a spatula fiber glass stripes (robbin) saturated with resin are placed between the face of the wall and the straps.

TR7

Horizontal steel straps (32 by 0.5mm) are placed around the wall and fixed with stud bolts 10mm of diameter, which goes through the wall. In each side of the stud bolts a washer and a lock nut are placed.

TR8

Devices consisting of a steel flat with a welded steel ring (chain link) are placed in both ends of the wall, double horizontal steel straps (16 by 0.5mm) are passed through the links and then tighten with a hand tool and fixed with double dead-end clamps.

TR9

Devices consisting of a steel triangular box with four welded steel rings (chain links) in both sides are attached at each corner of the wall. Diagonals steel straps (16 by 0.5mm) are passed through the links and then tighten and fixed as in TR8.

TR10

The same as TR8 except that plastic straps (16 by 0.8mm) are used instead of steel straps.

A summary of the test results of the first stage is presented in Table 1.
Shear stresses were computed with the expression (1):

$$\nu = \frac{P}{dt}\ (10^{-3}) \qquad (1)$$

Where ν is the shear stress in MPa; P is the maximum load applied to the specimen in kN; d is the length of the diagonal in which the load is applied in m; and t is the thickness of the specimen in m.

To evaluate efficiency of each method the index I is introduced which is computed as: for cases of repair (I_1), the ratio of the shear stress obtained from test in the repaired specimen and the shear stress of the corresponding original specimen; for cases of strengthening (I_2), the ratio of the shear stress obtained from the test of the upgraded specimens and the average of shear stress of all original specimens (0.507 MPa). Materials and workmanship used to construct the masonry specimens were the same as in the local construction practice. As a result substantial variation among the pair of specimens of the same kind was encountered. In order to evaluate the variability nine specimens were considerer in the second stage instead of two.

From Table 1 it can be seen that all of the methods comply its purpose because the strength is recuperated ($\overline{I_1}$ >1.0) and in several of the methods a significant strength increment was obtained: more than 1.3. The methods with greater $\overline{I_1}$ are: TR2, TR9 and TR10.

In the same way, from Table 1 it can be seen that all the methods represent an increment in strength with respect to the average of the original specimens, with a minimum of $\overline{I_2}$ =1.3 and a maximum of $\overline{I_2}$ = 2.45. The methods with greater $\overline{I_2}$ are: TR2, TR6 and TR9.

To have more elements for decision, the factor of the cost (labor and material) was included. The cost per surface unit (m^2) for each of the methods is shown in Table 1. The maximum is 7.34 USD/ m^2 and the minimum 1.16 USD / m^2.
Other criterion for decision was the level of workmanship required for each method. Three levels were defined: Level 1- Time of application per m^2 is no more than 25 minutes and no specialized workmanship is required; Level 2- Time of application per m^2 is no more than 45 minutes and any person can do it; Level 3- Time of application per m^2 is no more than 90 minutes and physical strength and skills for application are needed. The level of workmanship for each method is included in Table 1. Relation of cost is calculated as the ratio of the cost in each case to the average cost.

Fort the case of repair, the three methods selected for the next stage of the study were: TR2, TR9 and TR10. The method TR2 has a good increment of strength, low cost and level 1 of swordsmanship, and for the others the recuperation of strength is significant while the cost and workmanship are mild.

Fort the case of strengthening the three methods selected were: TR2, TR4 and TR9. Method TR2 for the same reasons as before, TR4 has the lower cost and TR9 is the one with greater increment of strength.

Table 1: Summary of test results, first stage

Method Identification	$\overline{I}_1$	$\overline{I}_2$	Cost USD/m2	Relation of cost (average)	Workmanship Level
TR1	1.23	1.94	7.34	1.50	3
TR2	1.39	2.45	3.49	0.71	1
TR3	1.18	2.1	5.82	1.19	2
TR4	1.21	1.74	1.16	0.24	1
TR5	1.23	1.32	4.25	0.87	1
TR6	1.35	2.37	6.65	1.36	1
TR7	1.07	1.84	6.33	1.29	3
TR8	1.18	1.96	5.16	1.06	2
TR9	2.16	2.31	4.99	1.02	2
TR10	1.39	1.3	3.71	0.76	1

Second stage

A total of 54 specimens were constructed; 27 were tested in their original state and then repaired with the selected methods and tested again; 27 were strengthened (without previous load) and tested. Nine specimens were tested for each method to estimate the variability in terms of the coefficient of variation (C_v). In Table 2 a summary of results for the cases of repair is presented including the relation of cost and the level of workmanship.

Table 2: Summary test results, 27 specimens "repair"

Method Identification	$\overline{I}_1$	C_V	Relation of cost (average)	Workmanship Level
TR2	1.62	0.27	0.71	1
TR9	2.17	0.23	1.02	2
TR10	1.03	0.34	0.76	2

A general observation is that the repaired specimens show significant recuperation of strength. Additional observations are as follows: a) Method TR2 (plastic straps) has a ratio of recuperation of strength of 1.62 in relation to the average strength of original specimens. The cost is the lower and the workmanship level is one. b) Method TR9 (steel Straps) has ratio of recuperation of strength of 2.17 in relation to the average strength of the original specimens. Cost is 43% higher with respect to the lower and the workmanship level is two. c) Method TR10 (plastic straps) has ratio of recuperation of strength of 1.03 in relation to the average strength of the original specimens. Cost is 6% higher with respect to the lower and the workmanship level is one. In relation to the methods of repair tested, TR9 is the most effective. Its characteristics compensate for its cost which is the highest of the three. This method was selected to be applied in the wall models of stage three.

In Table 3 a summary of results for strengthening cases is presented. The behavior of all three methods is satisfactory because an increment of strength is obtained. Additional observations are as follows: a) In method TR2 the ratio of increment of stress is 1.31. The cost is reasonable and the workmanship level is one. b) Method TR4 is the least expensive of all and workmanship level is one. However the ratio of increment of stress is low (1.09). c) In method TR9 the ratio of increment of stress is 1.94. The cost is high and the workmanship level is two.

Table 3: Summary of test results, 27 specimens "strengthening"

Method Identification	$\overline{I_2}$	C_V	Relation of cost (average)	Workmanship Level
TR2	1.31	0.17	0.71	1
TR4	1.09	0.20	0.24	1
TR9	1.94	0.07	1.02	2

In the case of strengthening methods, TR2 was selected for the next stage because it represents a balance in the three parameters studied: strength, cost and workmanship level.

Third stage

Methods TR2 and TR9 were applied on wall models 2.60 m in length and 2.30 m high. Two of the models were constructed as confined walls with reinforced concrete elements at the perimeter. The size of the confinement elements were 0.12m by 0.15m with four 10mm diameter deformed steel bars and stirrups spaced 0.25m made of 6mm plain bars, see Figure 2. The nominal yield stress of the corrugated bars was 412MPa and for plain bars 245MPa, concrete compressive strength was 24.5MPa. The other two models were constructed as non-reinforced walls. However, for the application of loads a C shape reinforced concrete element was added at the upper part of the wall with the same characteristics as in previous model, see Figure 3.

Fig. 2: Confined masonry wall

Fig. 3: Unreinforced masonry wall

Horizontal loads were applied in the plane of the wall models at the upper edge. The models were tested under reversing cyclic loads to increasing lateral deformations until failure. Vertical load simulating a dead load effect was applied at the top of the walls.

Wall models tested were identified as fallows

MS-01: without confinement, original
MC-02: with confinement, original
MS-F1: without confinement, strengthened
MC-F2: with confinement, strengthened
MS-P1: without confinement, repaired
MC-P2: with confinement, repaired

Tests MS-01 and MS-P1 were made on the same wall model, first tested in its original state and then repaired and tested again. The same for tests MC-02 and MC-P2. In models for tests MS-F1 and MC-F2 the strengthened methods were applied without previous damage and then tested. In each test the hysteretic behavior was tabulated and plotted (level of load in kN in the vertical axis and drift m/m in the horizontal). The main parameters to describe the structural behavior of the walls were obtained: ductility, as the ratio of maximum drift to the drift corresponding to the first crack; energy dissipation, the area within the hysteretic loops; degradation of the capacity as the ratio of the maximum load in one cycle to the next; stiffness degradation, the change in slope from one level of load to another. Calculations were made from consecutive cycles at the same drift as well as the total change of the last cycle in relation to the first cycle.

Figure 4 shows the hysteretic behavior of the test MS-01, the behavior was practically elastic in the first four cycles, the first crack appear in the sixth cycle and from this point inelastic behavior was observed, the test was continued until the maximum load (60 kN) was reached at a drift of 0.30% and diagonal cracks 7mm wide were observed. Ductility was 1.33 and the global energy dissipation 1753 kN-mm. The model was returned to the condition of zero displacement, then repaired with method TR9, and then tested. The corresponding test is MS-P1 which hysteretic behavior is shown in figure 5. The asymmetry observed is due to the damage in the original test, diagonal cracking was more severe in the direction of pull. The model presented a ductile behavior with maximum drift of 0.0113 and ductility of 4.5. Cracking does not increase respect the original test, the existing cracks opens with the application of load but closed again with loading in the other direction. The accumulated dissipation of energy was 11710 kN-mm. In Figure 6 the envelopes of tests MS-01 and MS-P1 are shown, it is clear that the repair method improve the behavior of the wall with more strength and ductility.

Original wall without confinement

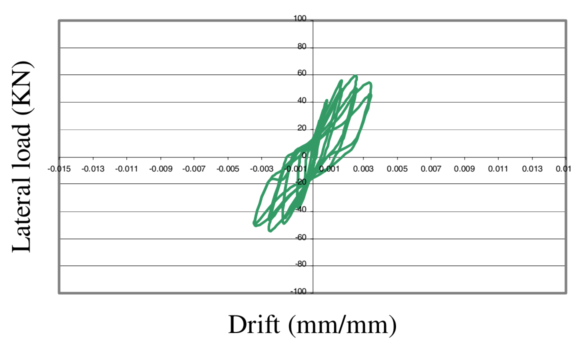


Figure 4. Hysteretic behaviors, test MS-O1

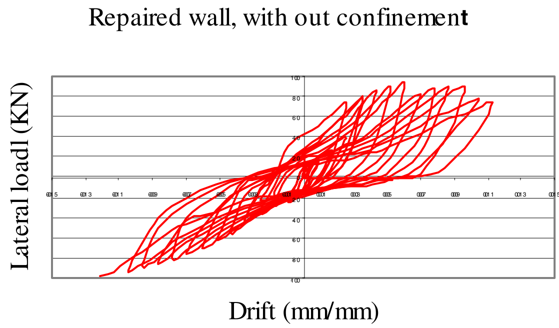


Figure 5. Hysteretic behavior, test MS-P1

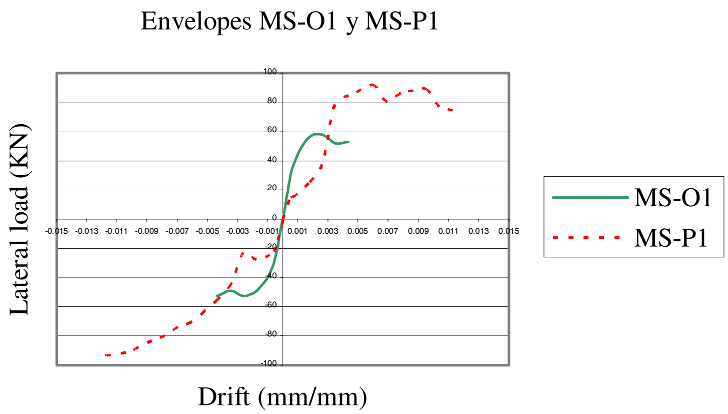


Figure 6. Comparison of envelopes, tests MS-O1 y MS-P1

Now for the wall with confinement and repaired with the same technique, the hysteretic behavior of the original wall (MC-02) is presented in figure 7, and the hysteretic behavior of the repaired wall (MC-P2) is presented in figure 8. In the original wall the behavior was practically elastic in the first six cycles, the first crack appear in the seventh cycle and from this point inelastic behavior was observed, the test was stopped when the maximum load was reached and severe diagonal crack appear. Maximum load was 66 kN at a drift of 0.4%. Ductility was 1.33 the global energy dissipation of 2088 kN-mm. The repaired model showed a symmetric behavior with stable loops, the ductility is 3.7 and the energy dissipation of 12253 kN-mm. The improved behavior of the repaired wall in relation of the original is evident in figure 9, where the envelopes are presented.

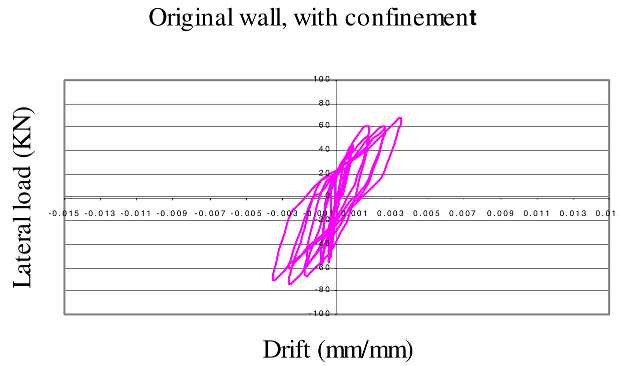


Figure 7. Hysteretic behavior, test MC-O2

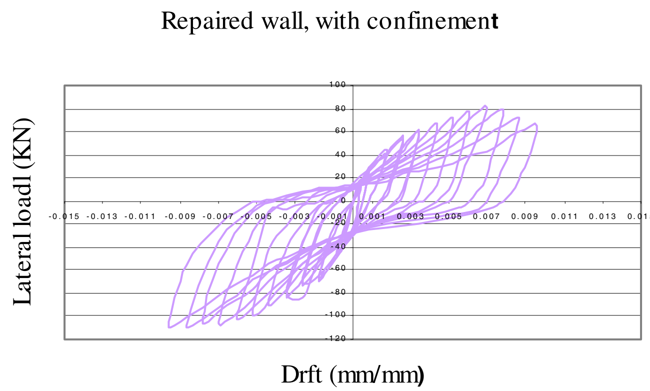


Figura 8. Hysteretic behavior, test MC-P2

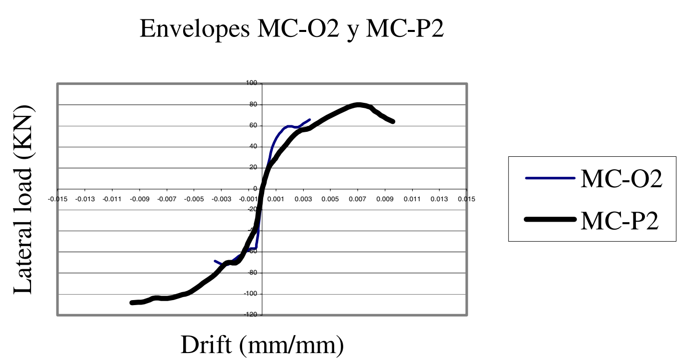


Figure 9. Comparison of envelopes, tests MC-O2 y MC-P2

For the strengthened walls good behavior was observed as can be seen in figure 10 for model MS-F1 and figure 11 for model MC-F2.

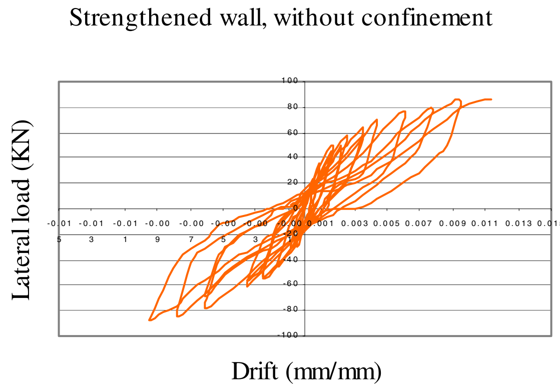


Figure 10. Hysteretic behavior, test MS-F1

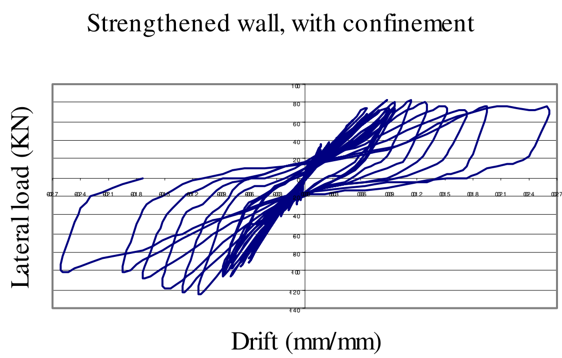


Figure 11. Hysteretic behavior, test MC-F2

A summary of the experimental results of the third stage is presented in table 4, significant increase of strength and deformation capacity of the repaired and strengthened models respect original walls is evident. The exact values of the increments in strength, ductility and energy dissipation are presented in table 5.

Table 4. Summary of results, third stage

Model	Ductility	Energy disipation (kN-mm)	Capacity degradatrion		Stiffness degradation		Global Stiffness degradation %
			Push %	Pull %	Push %	Pull %	
MS-O1	1.33	1753.27	9.52	6.50	14.04	0.00	65.00
MC-O2	1.33	2087.66	0.00	4.73	3.20	15.38	62.71
MS-F1	3.25	4988.59	0.00	0.00	9.25	1.90	76.90
MC-F2	7.50	24983.62	4.40	6.97	3.79	6.37	43.12
MS-P1	4.50	11709.90	12.00	0.00	4.65	0.94	54.86
MC-P2	3.70	12252.32	2.30	0.00	2.23	0.70	63.70

Table 5. Comparison of results respect original walls

Increment	Wall with confinement		Walls with confinement	
	TR2	TR9	TR2	TR9
Strength	1.49	1.59	1.26	1.21
Deformation capacity	3.85	2.35	2.50	2.00
Ductility	2.50	3.38	7.52	2.78
Energy Disspation	2.10	4.93	11.97	5.87

These results were compared with other studies on methods for the rehabilitation of masonry walls. Pineda [9] and Zepeda [10] reports data on walls repaired with mortar jacketing reinforced with wire mesh, Alcocer [11] makes a summary of several techniques. Facher [12] reports data on walls repaired with resin injections and fabrics of composite materials, Ehsani et al [5] evaluate the shear stress on elements with fibers of composite materials. Lissel and Gayevoy [13] report a state of the art review on the use of FRPS in masonry. With this information table 6 was prepared which shows the comparison of different repair techniques including the proposed in this paper. The most important parameters of structural behavior as well as the relative cost of replacement of damaged walls are inspected. Computed cost include: demolition of the damaged wall, removal of debris and construction of a new wall. In comparison with the techniques here introduced, mortar jacketing reinforced with wire mesh gives more capacity and stiffness but less ductility, and cost is appreciably grater; resin injection does not gives better results besides cost is greater. FRPS and other composite materials may give more strength but no more ductility and stiffness, and cost involved is quite greater. Thus the techniques here introduced and investigated have potentiality for application in masonry buildings especially in low cost housing.

Table 6. Comparison of methods

Method	Comportamiento			Cost respect of hat of replacement
	Strength	Stiffness	Ductility	
Straps	1.21-1.59	0.8-1.0	2.5-7.52	0.3-0.44
Jacketing	1.2-2.0	1.2-1.4	2.0-2.5	0.8-1.4
Injetion	0.8-1.0	0.8-1.0	0.9-1.2	1.0-2.0
Glass Fibre	1.2-2.0	0.8-1.0	0.9-1.2	1.0-1.4
FRP	1.3-2.5	0.8-1.0	0.9-1.0	1.8-2.2

The effectiveness and general observations of the repair and strengthening methods detected in the previous stages can be extended to the walls. As part of this stage it was possible to propose guidelines for the design and application of the methods studied. Details of these guidelines are presented next.

DESIGN AND CONSTRUCTION GUIDELINES

The principal steps to practical application of methods for the repair of masonry walls are:

a) For any of the methods intended for application to damaged structures, the first step is to survey and classify the existing damage. In Table 7 a general criterion for classification of damage in masonry walls is presented.

Table 7: General criterion for classification of damage in masonry walls.

Type of damage		Limits
Low	LD	Cracks of less than 3mm wide
Moderate	MD	Cracks of 3mm to 6mm wide. Maximum deviation from the vertical of 15mm or a drift of 0.004
Strong	StD	Cracks of 6mm to 10mm wide. Maximum drift of 1% of the wall height
Severe	SeD	Cracks and openings of more than 10mm with possible loss of material. Maximum drift of more than 1% of the wall height.

It is recommended that method TR2 be applied to walls classified as MD and to apply method TR9 to StD and SeD, while walls classified as LD only local repair is recommended. The following explanations refer only to method TR9.

b) The number of bundles of steel straps required is obtained by equation (2):

$$N_B = \frac{\nu L t}{N_T F \cos\alpha} \qquad (2)$$

In which α is the inclination angle of the straps; L is the length of the wall; t is the thickness; N_T is the number of straps in each bundle and F is the design strength of each strap.

For example for the wall tested:
ν= 0.34Mpa; L= 2.6m; t=0.12m; α=41.5° ; N_T= 4 (double strap in each face), F_{max}=12260N; with reduction factor of 0.8; F= 9810 N; applying Eq. (2) gives $N_B = 3.6 \approx 4$ bundles

c) Application

- Preparation of steel angles with welded steel rings (chain links).
- Attachment of the steel angles at each corner of the wall.
- Double steel straps are passed through the links
- Steel straps are tightened and fixed with double dead-end clamps.

The principal steps to the practical application of methods for the strengthening of masonry walls are:

a) In cases where damage is not present but the strength of some or all of the walls may be insufficient, the first step is to evaluate the structure for the seismic forces expected in the zone. This can be done with a suitable computer program or a simplified direct method of distribution of lateral forces. The walls with insufficient strength are identified and the extra amount of shear stress required for each is estimated. With this, the most adequate strengthening method is chosen. The following explanations refer to method TR2.

b) The number of bundles of plastic straps required is obtained with equation (3):

$$N_H = \frac{\nu' L t}{N_T F} \qquad (3)$$

In this case ν' is the shear stress required in addition of the existing, the other terms are similar to the previous case.

For example for the wall tested: ν'= 0.34MPa; the strength of the plastic strap is 2520 N, so the design force is: F= 0.8(2520)= 2017 N; applying equation. (3) gives $N_H = 13.28 \approx 14$ bundles. With a uniform distribution, the spacing of bundles is: S_H=2.3/14=0.16m

c) Application

- The bundles of plastic straps (polypropylene made of recycled plastic, used for packing) are placed around the wall. When necessary perforations to pass the strap are made at the edges of continuous walls.
- The straps shall be placed so one of the ends can be tightened with a special tool.
- Use two double dead-end clamps to fix the straps with the clamping tool.
- Cut fiber glass strips 10mm wider than the plastic strap. With the aid of a spatula, the fiber glass is placed between the face of the wall and the straps.
- General use resin is then applied to the fiber glass until saturation.
- Finally, the resin is allowed to cure for at least 72 hours.

More information regarding the design procedure may be consulted in Carreón [14] and Ramírez [15]

CONCLUSIONS

Ten methods for repair and strengthening of masonry walls were studied experimentally. The methods have the special feature of utilizing low cost materials which are easy to obtain and to place. Some of the methods require special accessories and tools but they are not sophisticated and can be easily acquired and used.

In the first experimental stage, it was established that all ten methods permitted recuperation of the original strength of damaged specimens and to increase the shear stress of strengthened specimens. Considering the increase in shear stress, the cost and the workmanship level the three best methods were identified: Repair TR2, TR9 and TR10; Strengthening: TR2, TR4 and TR10.

In the second stage, additional tests were carried out on the three most effective methods in order to obtain reliable estimations of the shear capacity implicit in each method. The variability in terms of the coefficient of variation (C_V) was similar to that obtained in general applications of brick masonry. With this was possible to propose a design criteria based on the consideration of a nominal shear stress of 0.343 MPa.

In the third stage four models of walls at natural scale were tested. Results show that the effectiveness and good performance detected in the previous stages can be extended to the walls. In this work is demonstrated that with the application of steel and plastic straps with the techniques proposed, a confinement action is attained which allow to the recuperation or increasing of the capacity and ductility of damaged walls, and also to the appreciable increase of capacity and ductility of vulnerable walls with propensity to suffer damage during earthquakes. In this work it is shown that the methods here introduced and investigated have potential application to decrease the seismic vulnerability of existing low income housing.

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