STRENGTHENING OF MASONRY WITH CONCRETE SLAB USING SPRING BOX AND HEAT STRETCHED POST-TENSIONING BARS

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ABSTRACT :

Non-engineered masonry houses constitute a major portion of the building stock in developing countries. Although masonry houses have major walls resisting lateral earthquake forces, the unreinforced nature and commonly weak inter-bonding and material properties of these walls make them vulnerable to earthquakes. A simple yet effective and economical strengthening technique was investigated for the seismic strengthening of masonry houses which have reinforced concrete decks. Placement of vertical post-tensioning bars between the floor and ceiling provided increase in strength multiple times the original capacity and improved behavior of masonry walls. A special spring box system was developed to maintain the major portion of the post-tensioning force in vertical tendons although almost all of the post-tensioning force is lost with the conventional systems as the walls pass their cracking capacity and move into nonlinear range. A heat stretching technique was developed to further reduce the application cost by eliminating complicated hydraulic based stretching tools or intermediate systems such as turnbuckle or bolted connections. A number of loading tests were conducted on ½ scale 6m long laboratory specimens to obtain level of improvement by comparing measured results. The findings indicate that rebar based post-tensioning is a very cost-efficient, effective, and simple way for strengthening against earthquakes for non-engineered masonry houses that have concrete slab or upper wall (spandrel) beams.

KEYWORDS: Masonry, post-tension, non-engineered, brick, rebar

1. INTRODUCTION

Masonry houses constitute a significant portion of existing houses in developing countries. According to Turkish Statistical Institute (TUIK) census 2000 data, about 51% of the existing building stock in Turkey is masonry type. Masonry houses are very strong against gravitational forces, but in large, they suffer during earthquakes due to their high inertial mass and brittle nature. When developing countries are located on seismically active zones, life and property losses during earthquakes are inevitable. May 1, 2003 Bingol, December 26, 2003 Bam, and October 8, 2005 Kashmir Earthquakes are recent catastrophic examples to non-engineered masonry house collapses.

General collapse mechanisms of masonry houses are well known, as numerous studied on the subject were conducted by many researchers. In general, the collapse of the masonry walls can be grouped under two headings for in-plane and out-of-plane failures. Commonly, in-plane failure of walls would trigger out-of-plane failure as well. Joint separation of walls at the corners would leave them all highly susceptible to out-of-bending failure if a rigid slab-roof is not present to form a diaphragm at the upper level of walls. The failure mechanism of in-plane walls may be again divided into three categories as rocking, diagonal shear, and horizontal shear failures. Generally, one of these mechanisms govern the failure as a function of the material properties, wall geometry (aspect ratio), and vertical force acting on the wall segment.

Although masonry houses can be prejudged as weak against earthquakes, subjective vulnerability assessment of structural system would reveal that some of the masonry houses actually have adequate strength against earthquakes. Provided that a) the walls of a low-rise masonry house properly join each other in perpendicular directions with proper intervals, b) rigid floor(s) exist and generate rigid diaphragm(s) at the top of the walls, c) window and door openings leave proper amount of continuous wall segments to carry seismic forces in both directions, d) soil – foundation conditions are favorable and e) material properties are better than minimum requirements, masonry houses remain in elastic range or at least suffer moderate damage without total collapse.

Some of the most commonly used strengthening methods for existing masonry can be itemized as a) placing reinforced plaster (e.g., using chicken wire with mortar) on the walls, b) placing buttress at the corners and unsupported walls in perpendicular directions, c) forming integral column-beam like members inside the walls by removing some of the existing wall material, d) fiber reinforced polymer (FRP) type strengthening, and d) post-tensioning in vertical and/or horizontal directions. Some of these methods may not be low-tech, easy to apply, or low-cost considering the complexity of application or material preparation such as concrete mixing, reinforcement placement, form work, hydraulic equipment, or FRP application.

This study targets to improve the pre-cracking strength and post-cracking behavior of masonry houses that have concrete slab, using simple-to-apply and cost efficient post-tensioning rods. Ordinary steel bars and plates are used for strengthening. The study involves simplistic tools such as applying post-tensioning force using bolted connections or pre-heat application on the rebar before connecting both ends on the structure. Using spring boxes to improve the post cracking behavior of the walls is also proposed since post-tensioning force can be easily lost due to minor crushing of the walls and/or yielding of the post-tensioning bars.

2. THEORETICAL BACKGROUND OF POST-TENSION APPLICATION FOR MASONRY

Theoretical background and application of post-tensioning using elastic straps for in-plane strength improvement was discussed by the authors (Turer et al.) on 1/10 scale masonry house tests. Furthermore, usage of scrap tire rings (STR) as post tensioning material was investigated on full scale masonry wall strips for out-of-plane bending direction (Turer and Golalmis). This study investigated usage of steel bars for post tensioning of masonry walls in their in-plane direction. Analytical and experimental studies show that brittle construction material used in masonry houses without reinforcement is weak in tension. Although, pure shear is applied on the walls, principle tension direction governs the failure mechanism by cracking and forming diagonal cracks on the walls. If vertical force acting on the walls is minimal and aspect ratio (height / length of the wall) is large, as in the case of single storey masonry houses with frequent windows and doors, the failure mechanism is the rocking and rolling motion of the walls. In that case, close-to-horizontal cracks at the bottom and top of the wall form and lead to overturning of the wall segment as a rigid body in its in-plane direction. This type of failure is dominated by bending action of the wall and relatively large tension forces at the wall supports, relative to the principle tension in the diagonal direction at the center of the wall.

If the walls are compressed in their vertical and horizontal directions, an even compression field is formed. Brittle materials such as brick, mortar, concrete, stone, glass etc. are generally much stronger in compression. Studies have shown that compression capacities of the indicated materials are commonly about 10 times larger than their tensile capacity. Therefore, application of post-tensioning force at a level of about half the compression capacity would shift the state of stress towards compression and delays formation of tensile cracks. On the other hand, in case of in-plane shear loading, the diagonal compression strut formation as well as vertical compression stresses generated by the overturning component brings additional compressive stresses which are accumulated on top of each other at the compression corner causing crushing failure. When vertical load carrying capacities of the walls are considered, 50% of the compression capacity reaches to impractically high forces. Therefore, vertically applied post-tensioning force should be carefully adjusted. Certain level of vertical compression field generated by post-tensioning would not only prevent premature failure of tension crack formations at the base or diagonal in the in-plane direction, but also enhances the out-of-plane bending capacity. Furthermore, the brittle nature of the unreinforced masonry (URM) wall may be transformed to horizontal shear failure, which is a mechanism that has relatively more ductile behavior and has better energy dissipating capability.

3. POST-TENSIONING APPLICATION USING BOLTS AND TEMPERATURE LOADING

One of the primary objectives of this study was to develop a post-tensioning based strengthening system which would be easy to apply and uses low-technology approach. Therefore, hydraulic jacks, load cell type sensors, complicated connection, and similar details were tried to be eliminated by using simpler, low-cost and low-tech details and methods at the expense of losing accuracy – precision. Two main approaches to apply post-tensioning were investigated by a) using bolted connections and b) heating bars prior to welding in place.

Bolted connections are easy to stretch post-tensioning bars using a threaded rod. Threaded rods can be welded on plain or deformed rebars and stretched using a simple nut and washer system as shown in Figure 1. The amount of post tensioning force can be arranged using the torque applied on the nut; however, a pre-calibration of the threaded rod – nut system is needed. The amount of torque to apply a certain amount of tensioning force in the rebar can be applied by using a torque wrench or simply measuring the applied torque using a hand wrench combined with a weighing spring placed in perpendicular direction to the wrench axis (Figure 1).

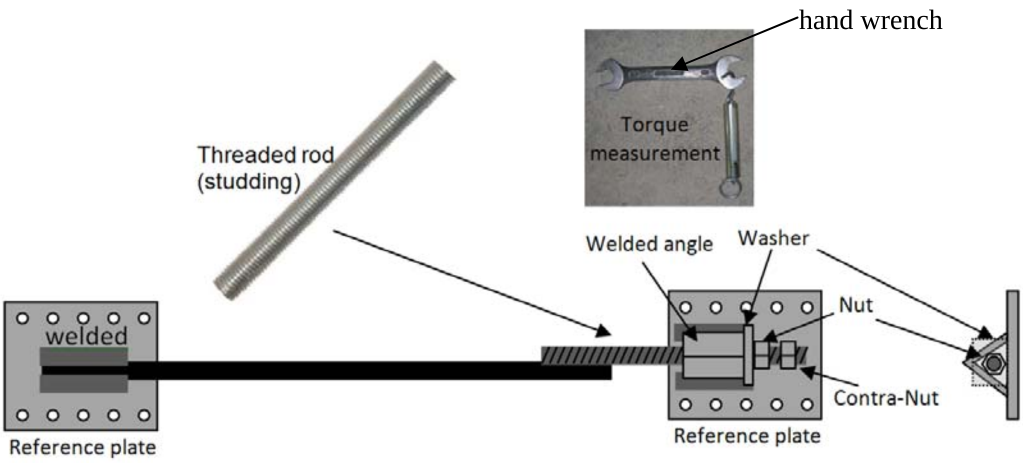

Figure 1 Schematic representation of post tensioning mechanism using bolts.

A general formula was developed to guess the amount of post-tensioning force as a function of the applied torque as shown in Eqn. 3.1, in which F stands for the necessary amount of force that needs to be applied on the wrench to create torque, P stands for the post-tensioning force in the rod, t is the spacing between each thread on the threaded bar, r is the radius of the threaded bar, η is the coefficient of friction between nut and the threaded bar, and R is the radius of wrench between centroid of the threaded bar and wrench end where force F applied by hand. Calibration studies have shown that η can be taken as 0.3; however, existence of oil on the threaded bar surface reduces the η value. Although oil existence or application may reduce the amount of torque applied by the wrench, it is important to lock the nut in place with a contra-nut to prevent post-tensioning losses due to loosening of the nut.

$$F = P \cdot \left(\frac{t}{2\pi \cdot r} + \eta \right) \cdot \frac{r}{R} \qquad (3.1)$$

Since the welded angle and torque applied nut may be too complicated for majority of the people who would be applying the post-tensioning on non-engineered masonry houses, an alternative approach was developed using heat based stretching. It was noticed that different levels of tensioning force might be applied by pre-heating the bars before welding. Experimental studies on heating of rebars (Figure 2) showed that significant axial force on bars can be achieved.

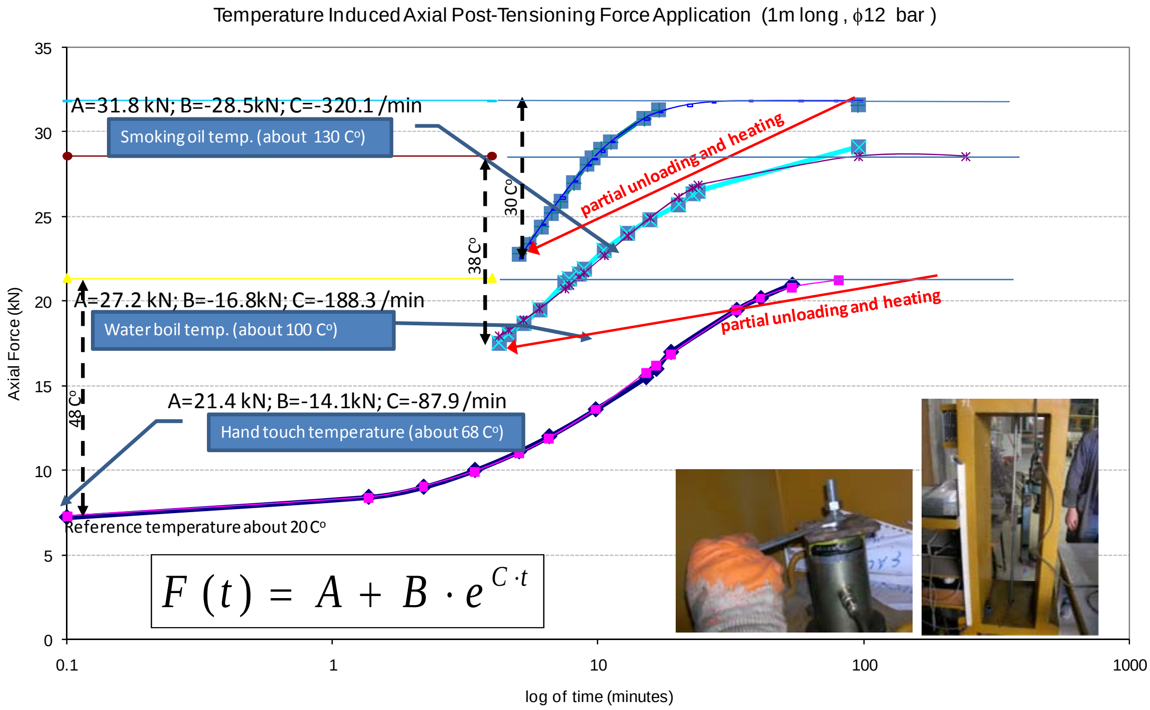

Figure 2 Temperature induced post-tensioning force application tests

For example, if a post-tensioning force in the range of 50% of the yielding stress is needed, half of the yielding strain may be easily imposed by temperature increase of the bar. If the yielding strain is 2000 με, then (assuming that thermal expansion coefficient $\gamma = 12$ με/C°), a temperature increase of (1000 με) / (γ με/C°), = 83C° in the bar temperature would be enough. Considering an ambient temperature of 20 C°, the post-tensioning bar temperature must be increased by 83 C° to 108 C°. The overall temperature of a bar can be measured by infrared based non-contact transducers; however, a primitive guess may be made by dripping water or oil on the heated post-tensioning bar surface. Boiling temperature of water can be taken as 100 C° while a range of different oil types would start to emit smoke when they reach to a certain temperatures (Table 3.1).

Table 3.1 Smoke emitting temperatures for common oils (Derrick Riches)

Oil/Fat	Celsius	Fahrenheit
Canola Oil - Unrefined	107°C	225°F
Safflower Oil - Unrefined	107°C	225°F
Sunflower Oil - Unrefined	107°C	225°F
Corn Oil – Unrefined	160°C	320°F
Peanut Oil – Unrefined	160°C	320°F
Olive Oil - Extra Virgin	160°C	320°F
Safflower Oil - Semirefined	160°C	320°F
Butter	177°C	350°F
Olive Oil - High Quality, Extra Virgin	206°C	405°F
Olive Oil – Virgin	215°C	420°F
Corn Oil – Refined	232°C	450°F
Peanut Oil – Refined	232°C	450°F
Safflower Oil - Refined	232°C	450°F
Sunflower Oil - Refined	232°C	450°F
Canola Oil - Semirefined	240°C	465°F
Olive Oil - Extra Light	243°C	470°F
Canola Oil - Refined	243°C	470°F
Avocado Oil	270°C	520°F

A few drops of water or oil can be conveniently found to roughly identify the temperature of the tensioning bar. Considering immediate losses due to constraints and long term losses, temperature based post-tensioning may target bar temperature in the order of 160 C^o. This study has shown that it may be possible to apply post-tensioning on conveniently found steel rebars using approximate temperature measurement techniques for non-engineered houses where minimum technological conditions do not exist.

4. EXPERIMENTAL STUDIES ON ½ SCALE HOUSES

Four tests on ½ scale and 6m long houses were constructed in the laboratory in order to test rebar post-tensioning based strengthening methods. The constructed URM lab house represented a single storey with two rooms; a basic housing unit constructed using hollow clay bricks, which is one of the most frequently used masonry construction material in Turkey. The basic properties of the test model was to have multiple openings symmetrically placed on either sides and have a concrete slab that connects all of the walls from above. The purpose of the test was to test effectiveness of rebar based strengthening on the brick masonry house and document relevant performance improvement. Symmetrically constructed walls on two sides of the house were aimed to generate symmetry in deformation and damage, while walls placed in perpendicular direction were planned to use for lateral stability. The width of the test house was kept low at 1 meter to save from the material and laboratory space since the primary concern was testing the house walls in their in-plane direction. The ceiling slab was pushed and pulled using a hydraulic piston operated by an electric pump for reversed cyclic loading of the house. The load was initially force controlled up to the level of initial cracking and damage formation; then, the displacements were controlled to observe the post-cracking behavior of the test house.

The strengthening plan for the masonry house was to first demonstrate the use of vertical post-tensioning on the capacity increase of the walls and then demonstrate the strength improvement for diagonal rebar bracing for the test house. An innovative approach using spring boxes were proposed to retain the post tensioning force on the rebars, which can be easily lost due to cracking of walls or yielding of the post-tensioning rebars. General behavior after strengthening was approximately predicted using simple relationships for design of strengthening on actual houses using the proposed technique.

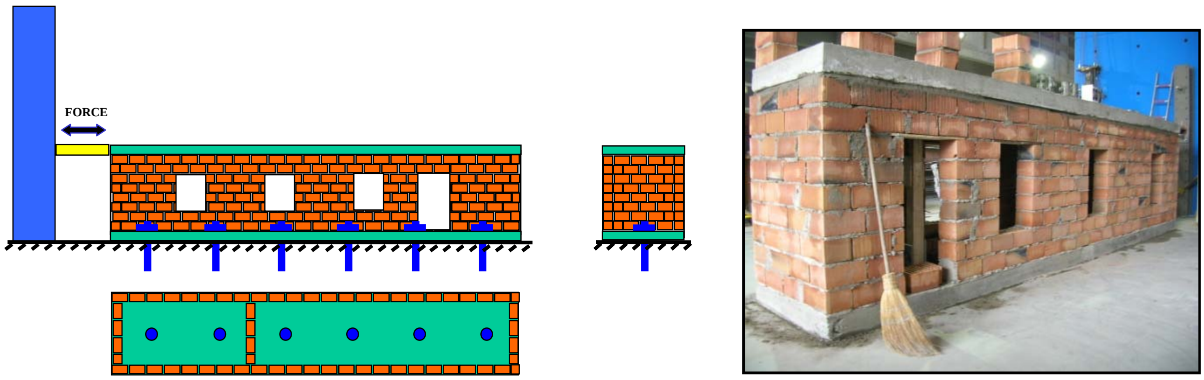

Figure 3 Half-scale brick masonry house model constructed in the laboratory

4.1. First test on reference house

The first test conducted on the masonry test house was on the nominal model. The initial strength of the house was recorded under reversed cyclic loading test and load-deformation graphs were obtained. The ultimate load capacity was about 60 kN and the dominant damage mechanism was overturning of the walls in the in-plane direction (rocking). Horizontal cracks at the top and bottom of the walls led to formation of diagonal compression struts, which generated a rotating mechanism around the opposing corners of the walls.

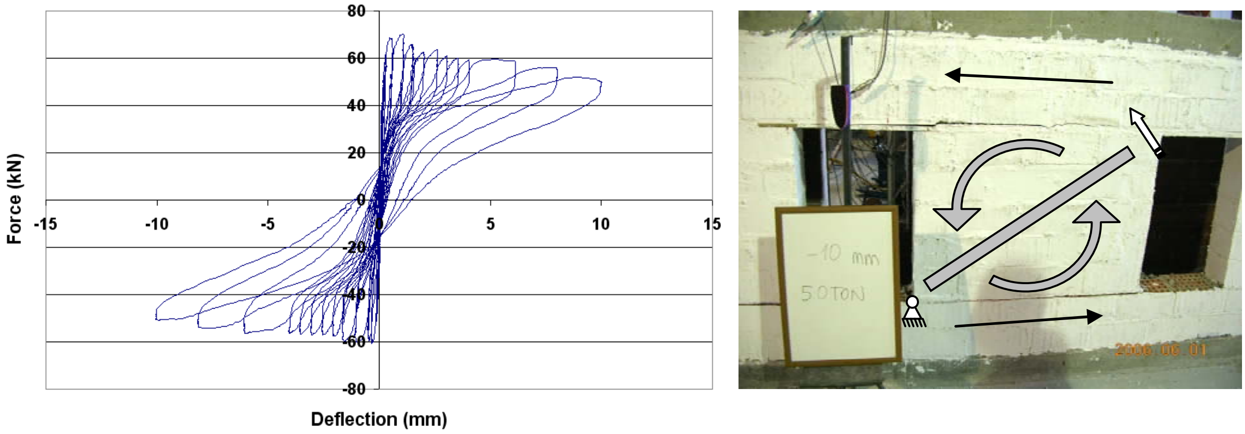

Figure 4 Load versus deflection curves of original (nominal) house

4.2. Reference house with additional static load on it.

As the rotating (rocking) mechanism shown in Figure 4 was evident, a simple restraining mechanism was thought to be the application of vertical compression force on the walls. The vertical compression on the walls can be applied using vertical post-tensioning or extra weight on the house. Although additional mass on the house would also increase the inertial forces generated during earthquakes, the test setup is loaded with about 5000 kg mass above the roof in order to see the actual effect on the already damaged test house.

Although the test house was initially damaged before the second testing, the lateral load capacity was improved to about %167 of the original house, from 60 kN to about 100 kN. The walls still rocked following the existing cracks that were generated during the first test; however, the rocking was more difficult since the vertical force on the walls were larger and acting in the opposite direction to restrain the rotating walls. The added mass was about equal to the mass of the existing house, therefore representing a second storey above the existing one.

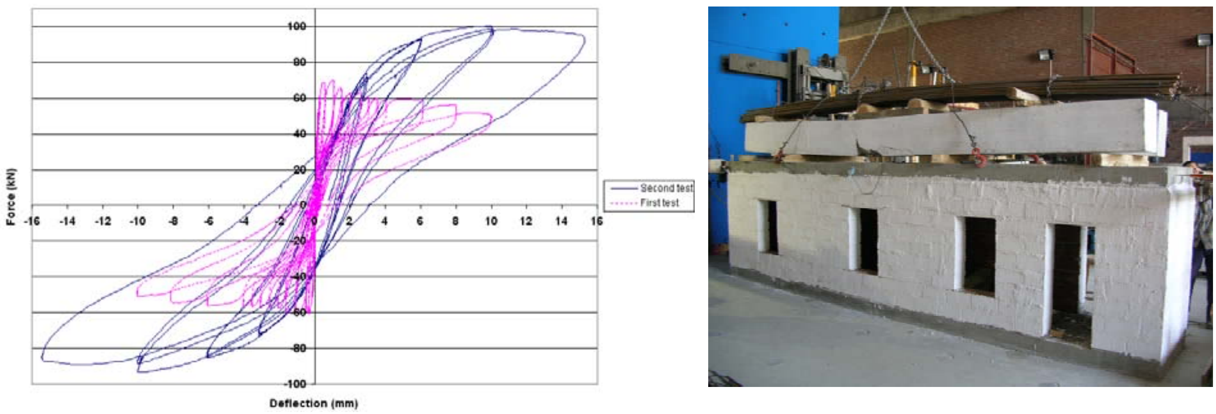

Figure 5 Load versus deflection curves of the original house with 5000kg mass on the roof

4.3. Application of vertical post-tensioning with rebars

The same (damaged) test house was used in the third test where total of 10 vertical rebars with ϕ12mm diameter were placed between the floor and ceiling slabs. The rebars were attached to the slabs using 10mm thick metal plates, which were anchored on the side surface of slabs using mechanical type steel anchor bolts. The mechanical bolts anchored in to the concrete can be found worldwide, which are first inserted into the drilled holes in the concrete and as the nut is tightened, a mechanism inside the drilled hole opens and locks the steel dowel inside the concrete. The locations of the vertical post-tensioning

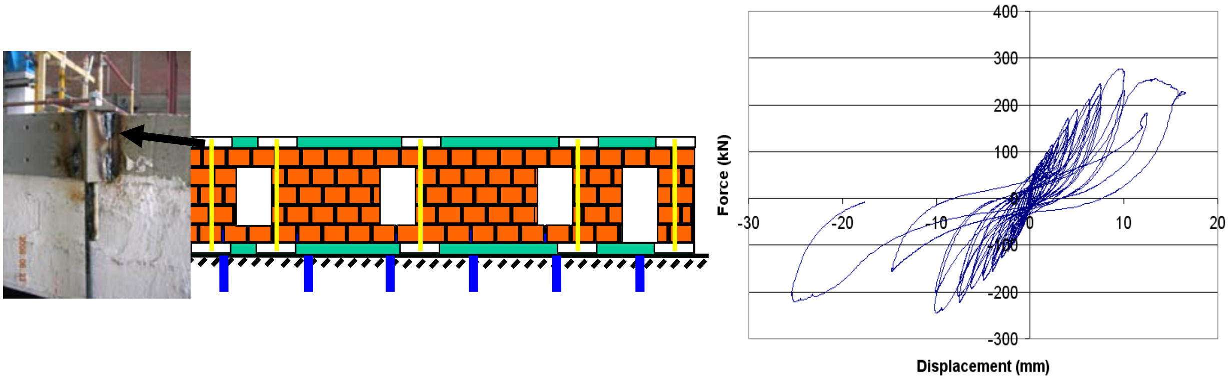

Figure 6 Load versus deflection curve of the vertically post-tensioned masonry house

rebars are shown in Figure 6. Assuming the floor and ceiling slabs form a close-to-rigid connection between the upper and lower edges of the walls, the vertical rebars were arbitrarily placed, except for not blocking the window or door openings and leaving room for cross brace rebar placement.

Post-tensioning bars located in the vertical direction were used to apply vertical force of about 20 kN on each bar for a total of 200 kN. Considering the 5000kg of mass generated 50 kN in the vertical direction, the applied force was about 4 times the former test. The ultimate capacity have reached to about 250 kN, which is more than 4 times the original capacity of 60 kN and about 2.5 times the 100 kN capacity with 5000 kg mass on the ceiling. Therefore, significant amount of capacity increase can be achieved by using vertical post-tensioning only, in single or two-storey non-engineered brick masonry type buildings.

The compression capacity of the mortar used in the walls was about 3 MPa, with accepted tensile capacity of 0.3 MPa. The total wall length was 11.4m with about 0.1m mortar width for a total mortar area of 1.14 m^2. Application of 200 kN vertical post-tensioning force in addition to the dead load of the 22 kN ceiling would generate vertical compression stress of 0.2 MPa, slightly below the accepted tension capacity (0.3 MPa) of the mortar at 7% of the compression capacity. Nevertheless, such an insignificant amount of vertical post-tensioning was enough to generate a capacity increase of 4 times the original capacity, altered the failure mechanism from rocking to diagonal shear cracking, and enhanced the ductility – energy dissipation capacity of the masonry walls in their in-plane direction.

During the test, it was noticed that the post-tensioning force in the rebars can be easily lost due to minor cracking and crushing of the URM walls. A mechanism was needed to keep the post-tensioning force close to constant although the vertical height of the walls was decreased during loading beyond the linear capacity. Spring boxes were attached at the ends of the rebars in series and had a selected spring stiffness adjusted such that deformation of about 20mm would generate the desired post-tensioning force on the rebar (i.e. 1 kN/mm). In this way, the force in the post-tensioning bar kept close to constant for small changes of the wall height in the post-cracking range.

4.4. Application of vertical and diagonal post-tensioning with rebars

Diagonally placed rebars with ϕ12mm diameter were attached between the floor and ceiling slabs with about 45^o inclination in addition to the vertically oriented rebars. The vertical post-tensioning was also applied using spring boxes. The cross-braces were post-tensioned by bringing the temperature of the bars to about 100 C^o (~80C^o × 12$\mu\varepsilon$/ C^o $\cong$ 960$\mu\varepsilon$) prior to welding two ends on the bolted plates placed at the sides of ceiling and floor slabs. The test house could not be fully loaded in the pulling (tension) direction since the actuator – slab connection was separated due to excessive force. The house was loaded in pushing direction beyond its ultimate capacity which has been recorded as 450 kN; a value that is about 7.5 times the original capacity (60 kN). Diagonal braces were yielded while vertical braces remained in elastic range.

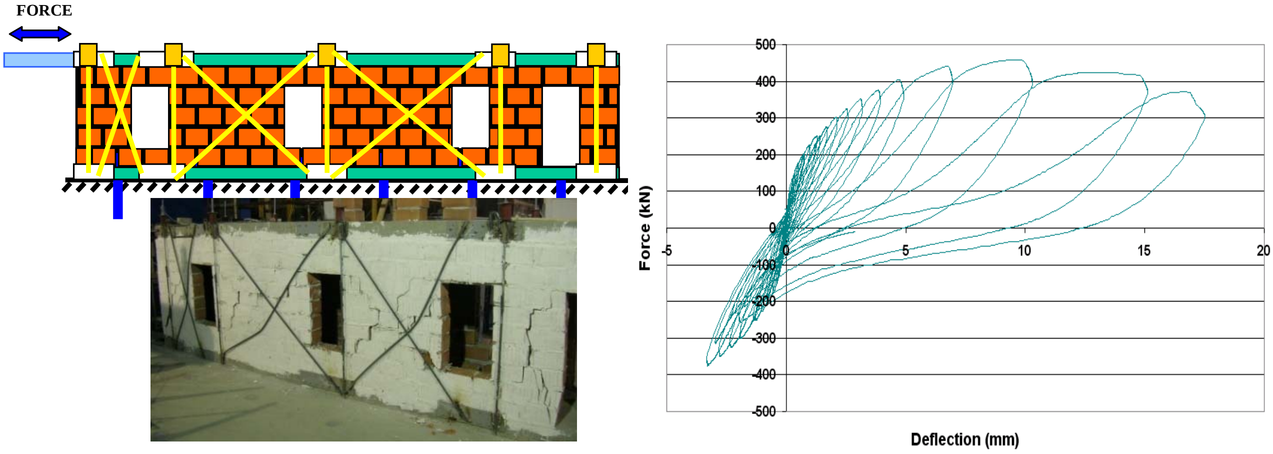

Figure 7 Load versus deflection curve of the vertically and diagonally post-tensioned masonry house

4.5.Simple engineering calculations

The number and variety of conducted tests on strengthening URM houses using rebar based methods was not enough to reach at generalized formulas. However, simple engineering calculations may be used to roughly predict the failure capacities of the walls. Assuming rocking mode of failure for the nominal house, the capacity of each wall may be predicted by using Eqn. 4.1, since shear stress at the free boundary of the wall is zero. The principal stress at the corner of the wall is shown in Eqn. 4.1, where σ_t is the tensile stress capacity; V and W are the horizontal shear and vertical forces acting on the wall, respectively; H is the wall height; B is the wall length; and t is the effective wall thickness. When multiple wall segments exist, as in the case of this study, the total horizontal and vertical forces should be distributed to each wall segment with respect to the their relative stiffness values and the wall under most unfavorable condition would fail first.

$$\sigma_t = \frac{V \times \left(\frac{H}{2}\right) \times \left(\frac{B}{2}\right)}{\left(\frac{B^3 \times t}{12}\right)} - \frac{W}{B \times t} \qquad (4.1)$$

When rocking mode of failure is not governing as in the case of vertical post-tensioning, diagonal shear (tension) failure capacity should be evaluated. A very rough approximation for the vertical post tensioning case horizontal load capacity (V_w) is obtained by $V_w = B \times t \times \sigma_t$ which assumes 45^o inclined cracking and obtained as 8.4m×0.1m×0.3MPa=252 kN (Figure 6). The maximum capacity for diagonal bracing case (V_T) can be roughly predicted by $V_T = A_{st} \times N \times f_y \times \cos(45) + V_w$, where $A_{st} \times N$ is the net diagonal steel area and f_y is the yielding stress. For the test house, $V_T = (\pi \times 6^2) \times 6 \times (450\text{MPa})/\sqrt{2} + 252\text{kN} = 468\text{kN}$ (Figure 7).

5. CONCLUSIONS

The experimental studies conducted on ½ scale 6m long URM single storey houses presented in this paper have shown that vertical post-tensioning and cross-bracing using ordinary rebars have significantly improved the ultimate capacity of the test houses up to 7.5 times the original capacity. Energy dissipation capability of the test house was also improved multiple decades with respect to the original test house. It was shown that application of post-tensioning force by simply tightening bolts or heating rebars is possible where minimum engineering technical tools are not available. Spring box attachment at the end of rebars would prevent premature loss of post-tensioning force. Proposed methods might be used to mitigate earthquake damages to non-engineered existing URM houses at developing countries.

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