Development of a Mortarless Post-tensioned Masonry Wall System

by

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ABSTRACT
An aging workforce of masons in the United States has challenged the masonry industry to develop innovative ways to construct walls by minimizing the physical efforts of the master masons. One inventor has proposed a mortarless wall system (FlexLock) to allow walls to be built primarily by mason apprentices under the direction of a master mason.

While mortarless systems are not a unique concept, few have gained wide acceptance. Most incorporate grout filled cores or surface bonding to provide the structural strength; the FlexLock system uses neither grouted cores nor surface bonding. New concrete masonry units (CMU) created using specialized manufacturing techniques are assembled dry-stacked and reinforced with post-tensioning.

This paper will describe the initial development of the system. In addition, the status of the test program will be presented.

1. DESCRIPTION

A patented system of mortarless post-tensioned masonry is being developed. The FlexLock system was conceived as an alternative to traditional masonry construction. It consists of CMU dry-stacked in running bond and post-tensioned. The first course is set in mortar for leveling purposes. The top of the wall is capped by a bond beam for anchorage of the post-tensioning tendons (Figure 1). Except for prescriptive requirements that require grouted reinforcement, the wall is built without mortar or grout.

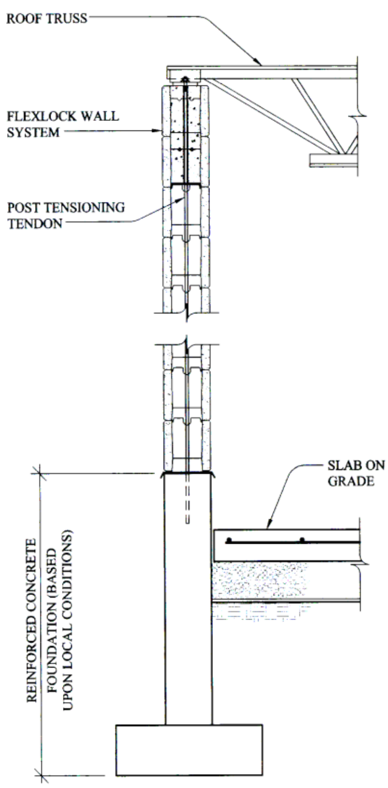
1.1 Development Issues

Significant issues must be overcome in the development of any new product. For this system, these include:

- Technical
  - Design and manufacture the units to accommodate dry-stacking.
  - Develop standard details.
  - Test system performance.
  - Evaluate the constructability of the walls.
  - Create analytical methods for design.
- Regulatory
  - Obtain approval by masonry standards and building codes.
- Social
  - Gain acceptance by architects, engineers, and contractors.
  - Gain acceptance by owners.

Only the technical issues regarding the units and their performance during testing will be addressed. The regulatory and social issues are not part of this discussion.

Figure 1 – FlexLock Wall System



1.2 Masonry Units

The stretcher units are modified 203 mm high x 194 mm wide x 406 mm long (8" x 7 5/8" x 16") and meet ASTM C90-99a standards. Unlike mortared units, the height and length of these units do not provide an allowance for mortar joints. Figure 2 shows the stretcher unit with its specialized web configuration that is intended to provide some interlock of the head and bed joints. The stretcher unit is a modified A block. It can be installed around the post-tensioning tendons without lifting them over the tendons; the orientation of every course alternates. Tendons can be spaced no closer than 406 mm (16") on center. The slot in the web is approximately 32 mm wide to laterally-restrain the tendons.

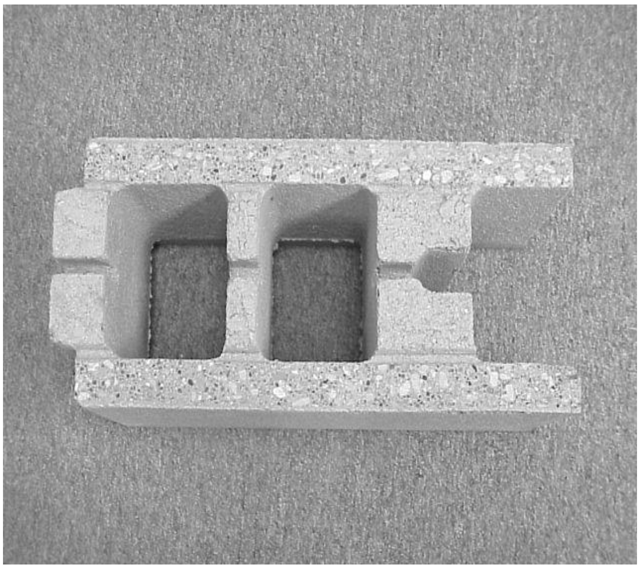


Figure 2 - Stretcher Unit

The webs are detailed to allow the use of the units as bond beams and lintel units as well as stretchers. Universal corner units create both corners and jamb ends.

The units must be in contact on their horizontal bedding joints to accommodate the post-tensioning. This requires closer unit tolerances than are normal for the manufacturing of masonry. Therefore, a calibration stage was introduced which sizes the height of the units after they are molded. The calibrator grinds the top of the units. The mold forms the bottom, sides, and the heads of the units. The tolerances obtained using the calibrator are approximately +/- 1mm.

1.3 Material Properties

All testing was performed under contract by the National Concrete Masonry Association of Herndon, Virginia. The initial units were tested for compression strength and absorption in accordance with ASTM C 140, “Standard Methods of Sampling and Testing Concrete Masonry Units.” Results of the unit tests are summarized in Table 1.

Table 1-Physical Properties of Concrete Masonry Units

Physical property	Test no. 1	Test no. 2	Test no. 3
Width, mm (in.)	193 (7.59)	193 (7.60)	193 (7.59)
Height, mm (in.)	203 (7.99)	203 (7.99)	203 (7.99)
Length, mm (in.)	405 (15.95)	404 (15.91)	405 15.94)
Minimum face shell thickness, mm (in.)	34 (1.33)	34 (1.32)	34 (1.32)
Density, kg/m^3 (pcf)	1586 (99.0)	1554 (97.0)	1560 97.4)
Net compressive strength of unit, N/mm^2 (psi)	40.06 (5810)	42.54 (6170)	30.61 (4440)

Table 1 values are based on the properties of saw-cut absorption, density, and compression specimens. Physical dimensions are based on full sized units.

The mix design was chosen for improved manufacturing and for light weight. Trial mixes are continuing using a variety of aggregates.

Masonry prisms were constructed to determine the dry stack compressive strength. Two units were gypsum capped, according to ASTM C 140, and then placed one atop another to form a dry-stack prism. This prism was then placed into the compression machine and loaded to failure. The test procedure followed ASTM C 1314, “Test Method for Compressive Strength of Masonry Prisms.” Figure 3 shows the dry-stack prism.

Figure 3 – Dry-Stack Prism

Only the face shells carry load, so the net area compressive strength can be determined using the average face shell thickness. The average net area was determined to be 272.3 cm^2 (42.2 in^2), and the average masonry prism strength was 18.31 N/mm^2 (2,655 psi). Figure 3 shows the typical failure mode of the prism, and Table 2 lists the individual prism strength tests.

Figure 3 - Prism Failure

Table 2 - Prism Test Results

Test no.	**Maximum Load kN (lbs)**	**Net Area Compressive Strength N/mm^2 (psi)**
Test no. 1	483.2 (108,620)	17.75 (2574)
Test no. 2	584.8 (131,460)	21.48 (3115)
Test no. 3	427.4 (96,080)	15.70 (2277)

2. PERFORMANCE TESTING – FLEXURAL

Flexural (out-of-plane) tests were performed on six wall samples that were 13-courses high and 3 2-units wide. The samples had either two or three tendons. Tendons were 11mm (7/16") diameter rods with a yield strength of 689.48 N/mm^2 (100 ksi) meeting ASTM 772 stressed to 23.13 kN (5,200 pounds). The post-tensioning stresses were approximately 0.4 to 0.6 N/mm^2 (55 to 82 psi). Figure 4 shows a panel under construction. Channels were used at the bottom and top to distribute the post-tensioning. The first course was mortared solid.

Figure 4 - First Course on a Steel Channel

Figure 5 shows the test setup where each wall was tested with third point loading. The panel was jacked up from the center from a structural steel frame. There are pipes used as hold downs at the ends. The underside of the first course and the channel are also visible.

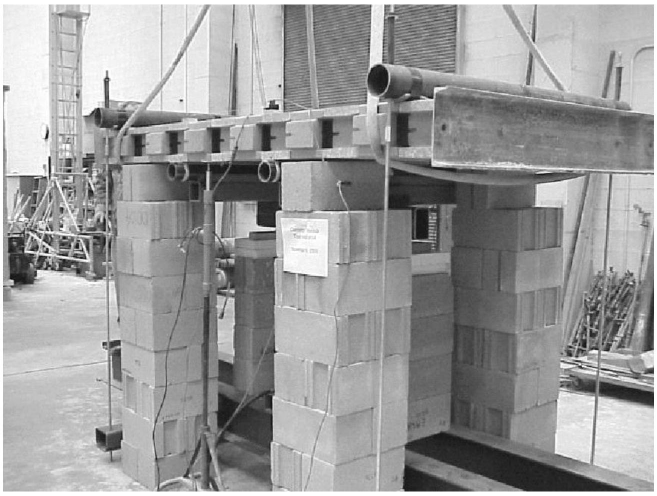


Figure 5 – Out-of-plane testing

Gauges were installed to measure deflections at the mid-point of the panel. An additional dash pot was installed on the top of the panel to measure the gaps created by the deflection. Figure 6 shows the load-deflection results of three tests. The load is the jack load which was distributed as two line loads on the panel. These results and those of the remaining three wall panels were generally very consistent. In addition, two panels were unloaded and reloaded in the elastic range for four cycles; the panels rebounded fully and had no strength degradation.

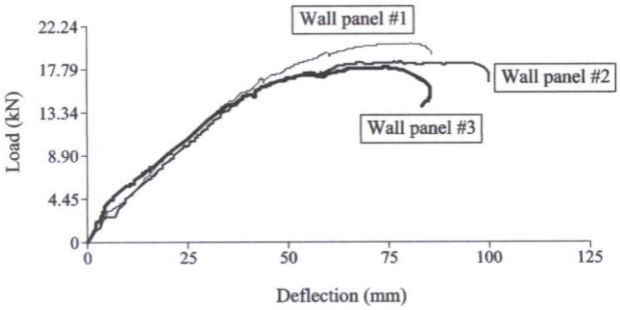


Figure 6 – Comparison of Wall Panels #1, #2, and #3

Figure 7 shows the panel at failure that occurred close to one of the load points. In general, the wall failed in an under-reinforced mode. The CMU was undamaged; there was almost no spalling of the face shells. However, the tendons were deformed as seen in Figure 8 where the wall has been disassembled. The deformation occurred where the tendons were in contact with the units. The units were generally undamaged and could be reused.

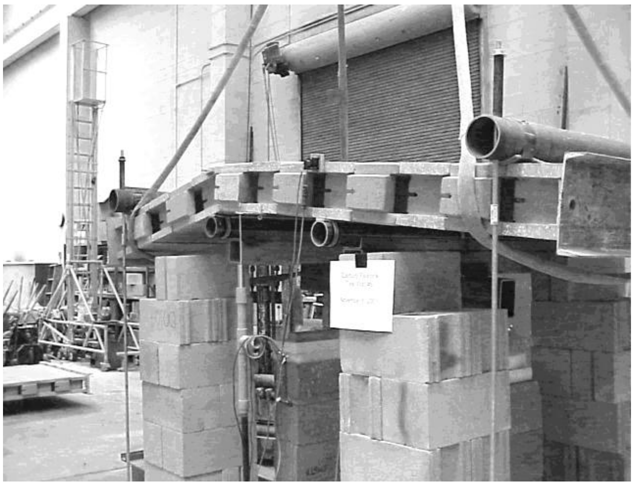


Figure 7 – Panel failure

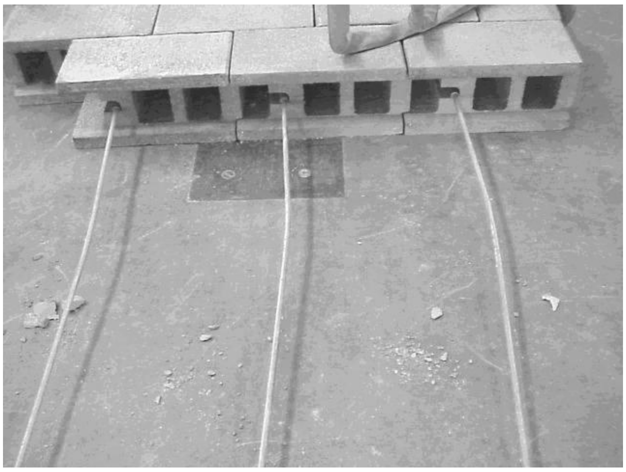


Figure 8 – Deformed tendons after testing

The elastic deflections occurred up to approximately 44 mm (1.75”) which represents approximately 1/61 of the wall height for loads of approximately 6.99 to 8.74 kN/m^2 (146 to 177 psf). For the typical design wall loads of 0.72 to 1.20 kN/m^2 (15 to 25 psf), the deflections are approximately 5 mm (0.18”) which represents approximately 1/578 of the wall height. The ultimate capacities approached 8.67 to 9.77 kN/m^2 (181 to 204 psf).

In the elastic range, some joints opened as much as 13 mm (2") but rebounded upon unloading. The joints opened first where the couplers came into contact with the inside of the slot in the web. Full-length tendons without couplers should perform even better.

In research with mortared systems using concrete masonry units [1], it was determined that the deflection ratio between cracking and ultimate was between 36 and 66, indicating a very large stiffness prior to cracking. However, in those tests the compressive stress due to the post-tensioning was approximately 4.62 N/mm^2 (670 psi). While the mortared systems appear to transition from the elastic range at cracking, they then experience a second linear range. The tests did not go through an unloading to verify if this second range was elastic also. Those tests did indicate that the stiffness of the second range is dependent upon the amount of post-tensioning. Assuming unloading would have shown the second range to also be elastic, the deflection ratio for elastic to ultimate would have been varied between 2 and 6.

In the mortarless system tested here, the post-tensioning was only 0.4 to 0.6 N/mm^2 (55 to 82 psi). The deflection ratio for elastic to ultimate was approximately 2 to 2.3, which compares favorably with the mortared tests.

Additional tests using clay masonry [2] were performed using post-tensioning stress levels of 0, 1, and 2 N/mm^2 (0, 145, and 290 psi). Those tests also show a similar bilinear response.

The mortarless system reacted similar to the mortared system in that there is a bilinear response. The first range of an mortarless system is due to overcoming the post-tensioning (see lower end of Figure 6). This creates an effective cracking moment, $M_{cr} = f_{pr}$ x S. In comparison, the first range of the mortared system is due to overcoming both post-tensioning and the mortar tensile stress. Here, the cracking moment is $M_{cr} = (f_{pr} + f_t)$ x S where f_t is the modulus of rupture for the mortar.

3. PERFORMANCE TESTING – SHEAR

Shear (in-plane) tests were also performed on an additional six samples. All of the samples were also 13-courses high. The widths were varied to represent three different aspect ratios (7 2 units, 42 units, and 32 units wide) Again, the samples had either two or three tendons. The panels were fabricated similar to the flexure test panels except that a whitewash was placed over the surface to allow the movement of the units to be seen. Figure 9 shows the test setup where a ram applied the shear load to the top of the walls. The test setup did not allow for cycle testing.

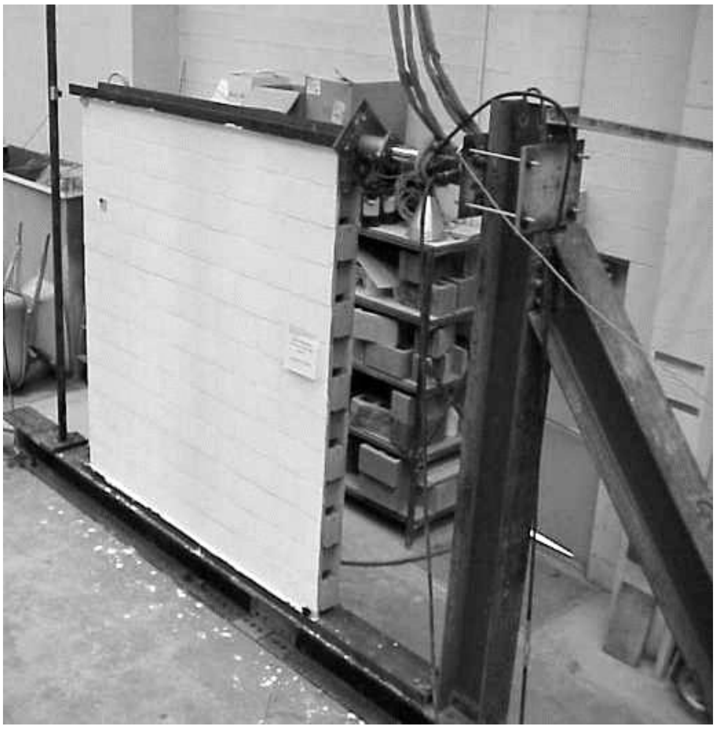


Figure 9 – Shear Testing

Figure 10 shows the crack pattern of one of the tests. The tendon locations are noted also. In general, the units remained tight in the area immediately around the tendons while step cracks and slippage occurred between the tendons. The step cracks are gaps in the whitewash.

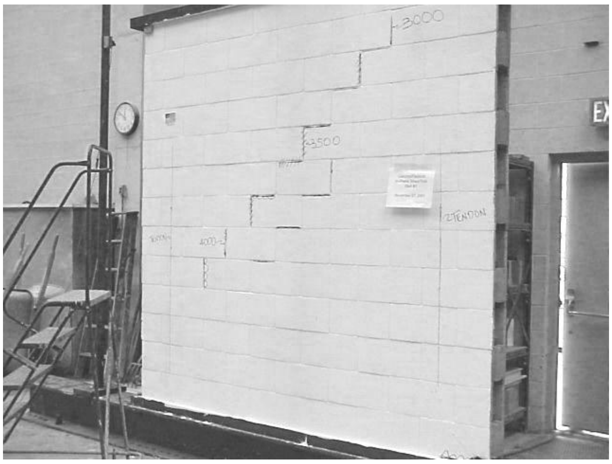


Figure 10 – Shear Cracks on Wall #1

Figure 11 shows the load-deflection results for one size panel. The load is the applied load by the jack. Shear wall #5 was 1.4 m (56”) long and 2.6 m tall and had two tendons. Shear wall #6 was the same size as #5, but had three tendons.

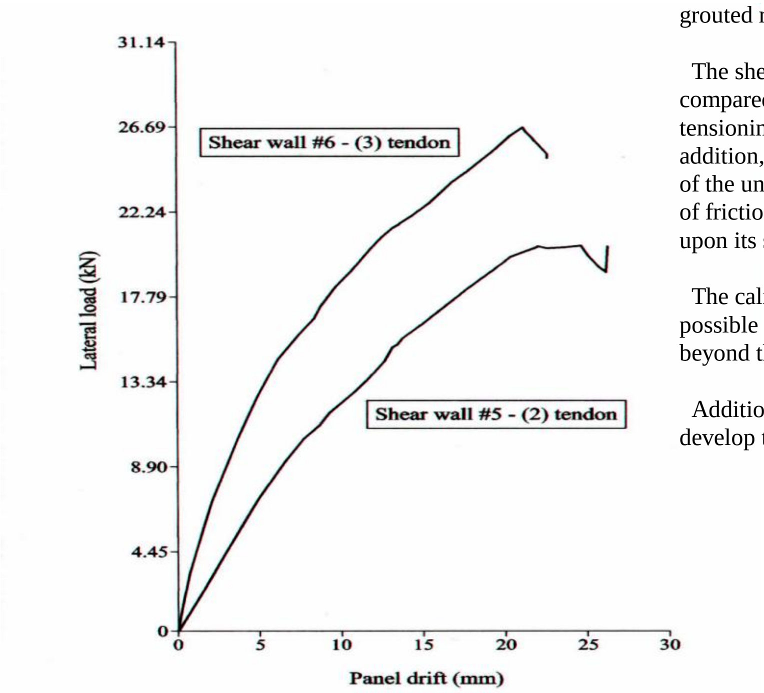


Figure 11 – Shear Results for Shear Panels #5 and #6

The shear results indicate there is an elastic range for the panels that quickly degrades due to sliding of the units. Conservatively, the drift is elastic for 8 mm (0.32”) for Shear wall #5 and 5 mm (0.2”) for Shear wall #6. These represent an elastic drift of approximately 0.3%. The calibration stage creates a smooth surface to the top of the units that effectively reduces the coefficient of friction between the units.

In the *MSJC Code* Section 2.2.5.2 (c) [3], the coefficient is effectively 0.45 for mortared masonry. Preliminary evaluation indicates that without mortar the calibrated units have a coefficient closer to 0.10.

In mortared systems with concrete masonry units, tests were performed on ungrouted walls [4]. These walls exhibited a response that was dominated by shear cracks across the face of the walls. Elastic drift levels were in the 0.1 to 0.2 percent range using axial load ratios of 0.06 to 0.02. While these walls developed significant shear strength, they did not exhibit reliable non-linear elastic behavior.

In the mortarless system tested here, the axial load ratio was approximately 0.03. The response was similar to the mortared system in that shear cracks developed as joints opened. However, these tests did not include cyclical loading. Additional testing is required, but indications are the system will perform like ungrouted, mortared systems.

4. CONCLUSIONS

Tests were performed with a relatively low amount of post-tensioning (axial load ratio of approximately 0.03). The CMU could have easily sustained 4 to 5 times the amount of post-tensioning used. However, the flexural tests indicate the mortarless post-tensioned system can be a viable system. While the tests results have to be compared to design codes, it is noticeable that the elastic range appears much greater than for a grouted reinforced wall.

The shear tests indicate the system has a lower strength capacity compared to mortared systems. However, the low degree of post-tensioning is the primary factor causing that reduction. In addition, the slippage of the units is greater due to the calibration of the units that produces a smooth bearing and lower coefficient of friction. Overall, the success of the system may be dependent upon its shear characteristics.

The calibrator technology makes the dry-stacking of units possible and has possible applications in masonry construction beyond the wall system presented.

Additional structural work and testing are still required to further develop the system for commercial use. These include:

- Additional tests with larger amounts of post-tensioning for axial load ratios of 0.05 to 0.15.
- Determine the coefficient of friction for calibrated units.
- Evaluate the shear capacity further.
- Test the system for cyclical loadings for seismic purposes.
- Develop design formulas and compare to existing codes.

ACKNOWLEDGMENTS

Thanks to Dominic Cerrato, inventor of the FlexLock Wall System, for permission to present the technical work being done for the development of the system. The data presented was obtained from a report “Flexural and In-Plane Shear Testing on FlexLock Concrete Masonry Panels” prepared under contract by the National Concrete Masonry Association of Herndon, VA, USA for Cercorp Initiatives Incorporated, 2002.

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