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OUT-OF-PLANE FLEXURAL STRENGTH OF REINFORCED DRY-STACK WALLS

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ABSTRACT
Dry-stack masonry systems are built without mortar between the units. Dry stacking reduces cost of labor and variability in construction and minimizes the required skilled labor. There are two subcategories of dry-stack systems: interlocked and surface bonded. Interlocking systems use the block geometry to connect one block to another and surface bonded systems uses a surface layer, usually cementitious in nature, to connect the blocks together. Depending on the load demand, dry-stack systems can be unreinforced (grouted or ungrouted) or reinforced and grouted. This article describes an experimental study where a dry-stack surface bonded wall system was tested for its out-of-plane flexural capacity. Six walls were constructed and tested. The walls were assembled with concrete masonry units, and, after stacking the blocks to form the walls, a glass fiber reinforced cementitious surface coat was applied to the walls. All walls were 2.44 meters by 2.44 meters and made with 200 mm thick units. Two walls were unreinforced and ungrouted, two walls were reinforced and grouted at 1.22 m on center, and two walls were reinforced and grouted at 0.61 m on center. A structural steel frame was assembled to support the walls and the walls were pinned at the bottom and top. The lateral load was applied to the face of the walls through a whiffletree system, which had two steel channels placed at third points (approximately 0.81 m and at 1.62 m from the bottom) along the length of the walls. The ultimate load on the walls were 4.8 and 5.7 kN for the unreinforced walls; 43.7 and 48.8 kN for the walls reinforced at 1.22 m on center, and 60.0, and 68.0 kN for the walls reinforced at 0.61 m. The results from the tests were compared and determined to be comparable to the design load calculated using the TMS 402 masonry code provisions.

KEYWORDS: *dry-stack, masonry, out-of-plane flexure*

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INTRODUCTION

Dry-stack masonry are systems are built without mortar between the block units. This is done to reduce cost of labor, reduce variability in construction from the mortar, and minimize the amount of skilled labor that is required to build a wall [1] [2]. Despite the lack of mortar, dry-stack systems have been shown to have similar axial capacities as that of traditional masonry [3] [4]. However, a disadvantage that exists with dry-stack systems is a higher manufacturing cost of the blocks to minimize irregularities that can cause stress concentration due to the lack of mortar to distribute the load [1]. The stress concentration caused by these irregularities can severely weaken the overall system.

Within dry-stack systems two subcategories exist, mainly interlocking systems and surface bond systems [1]. Interlocking systems utilize the geometry of the blocks to connect one block to another, which helps align the blocks for easier construction [5]. Unfortunately, these systems vary depending on the block that is used, which makes it difficult to develop design parameters for them. Surface bonded systems are dry-stack systems that connect the blocks through a surface bonding layer, which is usually cementitious in nature. The advantage of evaluating these systems is that the surface bonding layer can be applied to a variety of systems and is easier to develop design standards.

Research that has been conducted on dry-stack systems has been mainly dedicated to interlocking systems. These include projects on the Azar system [6], the Sparlock system [7], and the modified H block or WHD block [8] [9], which were tested for their axial capacity. Dry-stack stone masonry walls [10] and HYDRAFORM dry-stack system [11] were evaluated for their in-plane shear capacity. However, little research has been conducted on surface bonded dry-stack systems for their out-of-plane flexure capacity.

OBJECTIVE

The goal of this research was to determine the out-of-plane flexural capacity of dry-stack, surface bonded walls. All the walls were tested to failure by applying a uniformly distributed load at the third points along the height of the walls on one of their faces.

WALL SYSTEM

The wall system used in this research is a dry-stack, surface bonded system. This system uses a set of blocks and a set of expanded polystyrene (EPS) insulation inserts. The system relies on a surface bonding layer for the physical connection between the blocks.

The block dimensions are similar to commonly used concrete masonry units being 200 mm x 200 mm x 400 mm, but the geometry of the block are different. The blocks have 3 rows of concrete with 2 rows of openings that provide space for grout, reinforcement, utility ducts, and insulation inserts. Figure 1 shows the different blocks utilized in the wall system.

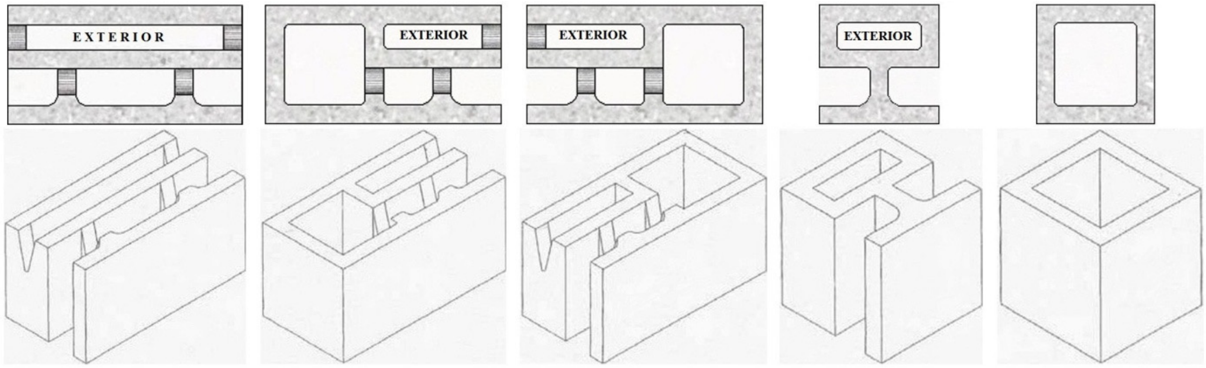


Figure 1: Dry-Stack System Blocks

The stretcher block is the most common block in the system and is used to span between corners. The left and right corner blocks are used at the corners where the wall continue around. The half stretcher is used when a full size stretcher is too long, and the half square blocks are used when the wall ends without continuing around a corner.

The EPS insulation inserts have two purposes: insulation for the building and to help align blocks during stacking. There are two types of inserts, large and small. The large inserts are used in all exterior openings. The small inserts are used in interior openings unless these openings are need for reinforcement and grout. The inserts help align the blocks as they are slightly taller than the blocks, and with the help of metal shims they reduce stacking problems caused by small imperfections on the block surfaces.

The surface coating is similar to mortar. It is a cementitous material with glass fibers included in the mix. The surface coating is prepared by simply adding water to the material and mixing it thoroughly. Two consistencies were prepared: one for the first layer, or structural layer, and one for the second layer, or outer layer. The first layer is thicker than the second layer, while the second layer has a greater amount of water added to allow the surface coating to be smooth and fill in any gaps of the structural layer.

WALL CONSTRUCTION

Wall construction consisted of block placement, grouting, and application of the surface coating. The blocks were laid on top of a steel channel that was used to secure the specimen during transportation and as part of the testing frame. After each course was laid, foam inserts were placed in their cells before the next course was laid. If the cells were to be grouted, no foam inserts were placed in the cells, instead reinforcement was placed in these cells. All reinforcing steel that was used was grade 40 steel. After 6 courses, a horizontal grout layer (bond beam) was poured as well as all vertical reinforced cells were grouted.

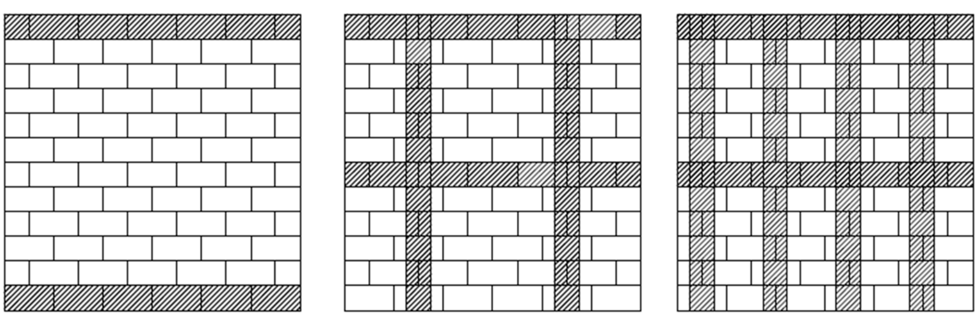
After the blocks were laid and grouted, the specimens were wetted down with a hose for approximately 10 minutes to prepare the wall for the application of the surface coating. The surface coating was applied in 2 layers. The first layer, was applied to the faces of the wall using a hawk and towel, and then spread out using a Darby. The thickness of the first layer was checked to ensure that it was between 3 to 5 mm. After the structural layer began to set, the second layer was applied using a hawk and towel. The surface was then troweled until smooth. The specimens were then kept wet over the next 24 hours and allowed to cure in the laboratory for 28 days. Figure 2 shows the different stages of construction.

(a) Blocks Being Laid. **(b) Application of Surface Coating** **(c) Curing**

Figure 2: Wall Construction Stages

WALL CONFIGURATION

Six walls were built and tested. The walls were built using full and half stretcher blocks and they were 2.44 meters tall by 2.44 meters wide. Walls #1 and #2 were ungrouted and unreinforced, except for a bond beam at the top and bottom of the wall to connect the wall to the footing and to the testing frame. Walls #3 and #4 were grouted and reinforced every 1.22 m on center both vertically and horizontally. Walls #5 and #6 also were grouted, but were reinforced 0.61 m on center vertically and every 1.22 m on center horizontally. Figure 3 shows the various wall configurations used.



(a) Walls 1-2 **(b) Walls 3-4** **(c) Walls 5-6**

Figure 3: Wall Configurations

TESTING FRAME

Figure 4 shows the frame setup for the out-of-plane testing. The wall was constructed on top of an inverted steel channel and an inverted steel channel was connected to the top of the wall. Two steel columns were attached to the strong floor in the laboratory with DYWIDAG bars that were then post tensioned to the strong floor. A top steel channel was then connected to the columns by four pins through slotted holes in the columns, and three steel brackets were welded to the bottom of that steel channel. In addition, a bottom steel I-beam was attached to the strong floor with post tensioned DYWIDAG bars.

Steel clevises were welded between the top channel and the channel on top of the wall and between the bottom channel and the bottom I-beam to allow out-of-plane rotation of the walls. The purpose was to simulate a pinned-pinned connection at the top and bottom of the walls.

Figure 4: Out-of-Plane Flexure Test Frame

The force was applied to the wall by means of a 444.8 kN capacity actuator. The actuator was attached to a built up whiffletree system. The frame consisted of steel channels connected to each other in such way to transfer the load from the actuator to the wall. The end of the frame had two steel channels, 0.81 meters apart, which pushed on the face of the wall. The steel channels were 2.44 meters long, the same width as the walls, and 0.20 meters wide to distribute evenly the applied load across the face of the wall without crushing the blocks. Figure 5 shows the loading system with the actuator and the whiffletree system.

The load was applied at the third points along the height of the wall. An array of displacement measuring devices were attached to the face of the wall to monitor the out-of-plane displacement of the wall. The load was monitored by the internal load cell of the actuator. All walls were tested to failure.

Figure 5: Loading System for Test

RESULTS

The applied load measured from the actuator was used to calculate the moment acting on the wall. The ultimate capacity as well as the theoretical yield moment of each wall is presented in Table 1. As expected, the capacity of the walls increased with the amount of vertical reinforcement in the wall. Figure 6 shows the typical failure of the walls. From general beam theory the moment should be highest between the two beams of the whiffletree system and it was there that failure was expected to occur. As expected the failure did occur between the two beams pushing on the wall, however the failure usually occurred generally close to one of the two beams.

Figure 6 Typical Wall Failure

Table 1: Summary of Test Results

Wall	Reinforcement configuration of the walls	Maximum Load (kN)	Calculated Mu (kN-m/m)	My (kN-m/m)
1	ungrouted	4.8	0.80	-
2	ungrouted	5.7	0.95	-
3	1.22 m x 1.22 m	48.8	8.17	7.2
4	1.22 m x 1.22 m	43.7	7.32	7.2
5	0.61 m x 1.22 m	68.0	11.38	9.6
6	0.61 m x 1.22 m	60.0	10.05	9.6

COMPARISON TO DESIGN STANDARDS

The values from the experimental results were compared to the calculated flexural strength using equation 1 and 2 [12]. In this equation φ is a reduction factor equal to 0.9, A_s is the area of the reinforcement in mm.^{2}, f_y is the yield strength of the reinforcement, d is the distance to the reinforcement from the extreme compression fiber in in., a is the depth of the equivalent compression stress block in mm, and b is the width of the section in question.

$$\phi M_n = 0.9(A_s f_y)(d - \frac{a}{2}) \quad (1)$$

$$a = \frac{A_s f_y}{0.8 f'_m b} \quad (2)$$

For the comparison, the following values were used: A_s = 64.52 mm^2 for 1.22 m x 1.22 m walls and A_s=129.03 mm^2 for 0.61 m x 1.22 m walls, f_y = 275 MPa, d = 133 mm, b=305 mm. which resulted in a = 6.86 mm and 13.97 mm for walls 3-4 and walls 5-6, respectively. Figure 7 shows all the results. The calculated flexural capacity of the unreinforced, ungrouted wall is zero.

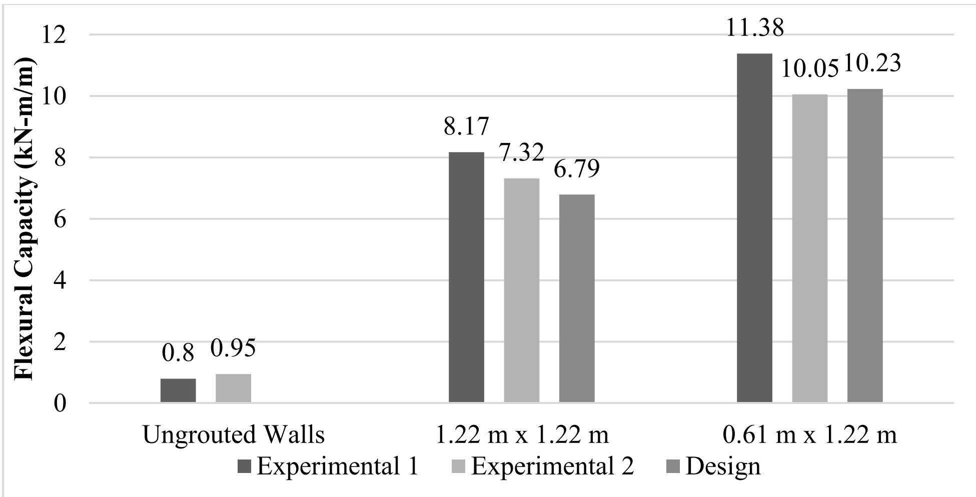


Figure 7 Comparison of Experimental Results to Design Calculations

As shown in Figure 7, the measured results from the testing surpassed the design calculations except wall 6. However, if the average of the experimental results are used, the average in all cases is higher than the calculated capacity. The lower capacity of wall 6 is probably just variability in testing.

Also, all the reinforced walls surpassed the theoretical yield moment capacity. Unfortunately, due to safety concerns the reinforcement was not inspected after the test. Having reached the theoretical yield moment it is assumed that the reinforcement did yield.

MODULUS OF RUPTURE

Using the results of the ungrouted walls, the modulus of rupture of the surface bond was calculated. The modulus of rupture was calculated using equation 3, where f_r is the modulus of rupture, M is the moment acting on the wall, c is the distance from the neutral axis to the surface coating, and I is the moment of inertia.

$$f_r = \frac{Mc}{I} \tag{3}$$

M was taken as the calculated maximum moment as presented in Table 1, c=9.87 cm, and I= 15118.77 cm^4. This resulted in a modulus of rupture of 520 and 620 kPa/m for walls 1 and 2 respectively.

The modulus of rupture in traditional masonry is dependent on the direction of tensile stress and the type of mortar that is used. When the tensile stress is parallel to the bed joints and the walls are partially grouted as in the experiment, the highest value of the modulus of rupture is 455 kPA for M and S type mortar. The surface coating resulted in a higher modulus of rupture in both unreinforced walls.

WALL DISPLACEMENT

In addition to the measured load acting on the wall linear variable differential transformers (LVDTs) were used to measure the displacement of the wall. At the center of the wall, four LVDTs were used and the average displacement measured between the four are presented in Table 2 for the maximum load. Figure 8 shows a typical load-displacement graph.

Table 2 Wall Displacement at Maximum Load

Configuration of walls	Max Load (kN)	Displacement at max Load (cm)
ungrouted	4.8	0.04
ungrouted	5.7	0.06
4'x4'	48.8	3.38
4'x4'	43.7	2.36
2'x4'	68.0	2.70
2'x4'	60.0	2.08

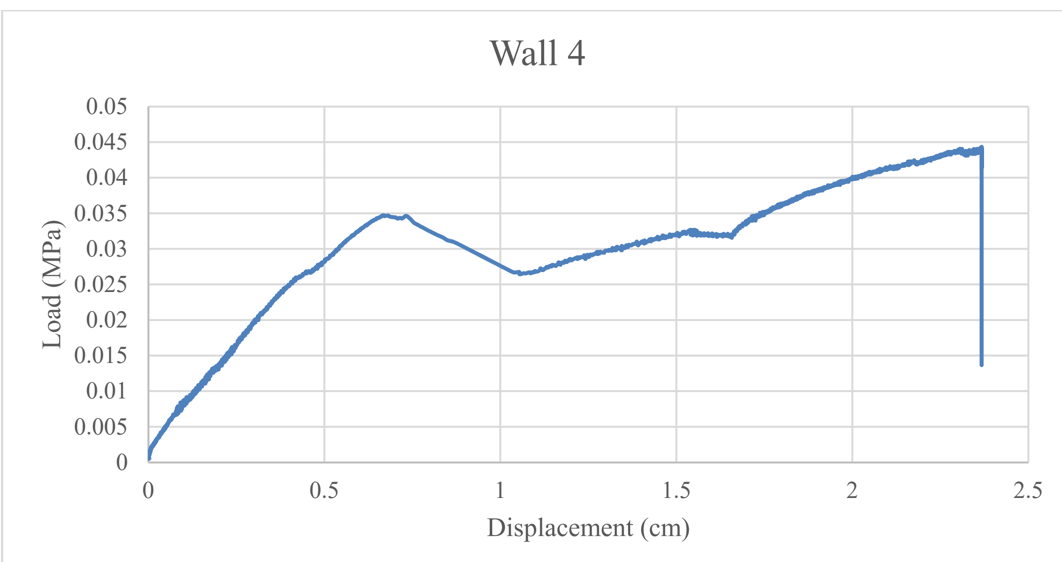


Figure 8: Load-Displacement Graph

The measured displacements were compared to expected displacement assuming a simply supported beam with two loads symmetrically placed. The calculated displacement was calculated using equation 4.

$$\Delta_{max} = \frac{Ph^3}{28EI} \quad (4)$$

In this equation P was the maximum load divided by 2, h was the height of the wall, E was the modulus of elasticity, and I was the moment of inertia, which is equal to 15118.77 cm^4. The modulus of elasticity was calculated using equation 5.

$$E_m = 900 f'_m \quad (5)$$

In this equation E_m is the modulus of elasticity, and f'_m is the compressive strength of the masonry which was taken as 10.34 MPa from testing of the dry-stack blocks. A comparison of the calculated displacement to the experimental results are shown in Figure 9.

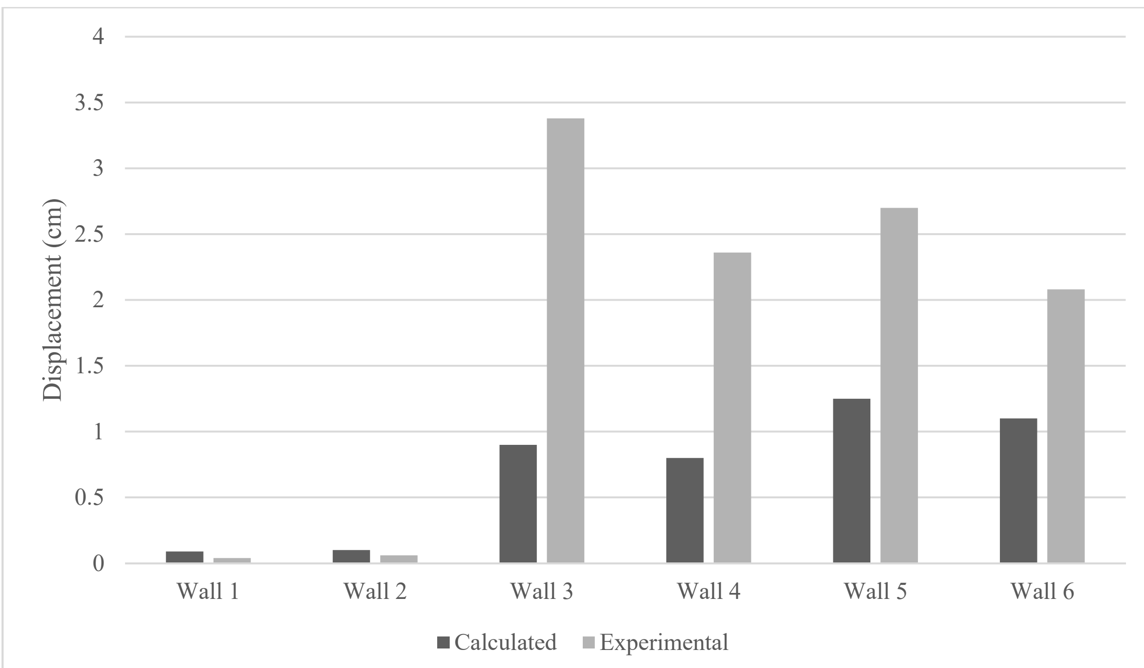


Figure 9 Calculated Displacement Compared to Experimental Results

As shown, the displacements measured during the experiments were higher than calculated. It is believed that the discrepancy derives from the modulus of elasticity. This value is an approximation that has seen some variation based on testing [12]. Also, the modulus of elasticity used was that for traditional masonry and may not be suitable for dry-stack systems. As reinforcement in both walls 3 and 4 are considered to have yielded the difference in displacement is due to variability in testing.

CONCLUSIONS

Testing was conducted on 6 dry-stack surface bonded walls to assess their out-of-plane flexural capacity. The capacities were then compared to the calculated capacity using the strength design method from TMS 402. The research showed that the current code method is capable of reasonably estimating the flexural capacity of the walls.

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