TANZANIAN CONCRETE MASONRY WALLS

Strength of Tanzanian Concrete

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Introduction and Background

The United Republic of Tanzania is in one of the most impoverished regions in the world. The Mbesese Initiative for Sustainable Development (MISD) is a nonprofit organization that hopes to combat poverty in Tanzania through education. The nonprofit's plan includes the development of a poly technical university. The construction of this university is to be done by local workers using locally available materials and methods. One of the local materials that will be used throughout the campus buildings is concrete masonry block. In support of MISD, the goal of this project is to replicate the composition of the concrete masonry blocks that are used in Tanzania and construct a wall to determine its strength. The walls will be tested for out-of-plane loading to establish a relationship between strength and stiffness, then compare tested values to predicted values using code-based design procedures. The testing is needed since the concrete masonry blocks made in Tanzania are made with different mix ratios of cement, aggregate, and water when compared with those commonly used in western countries such as the United States.

Objective

The goal of this project is to create masonry walls that replicate the construction methods used in Tanzania, including but not limited to blocks, pattern, and reinforcement placement. The replica masonry walls will then be tested, and the out-of-plan strengths and deflections will be recorded. To achieve this concrete masonry blocks will be made that replicate those used in Tanzania. These blocks will be tested to determine the strength of the blocks and see if an accurate prediction is possible to calculate. Then the blocks will be assembled into two different walls in a method replicating those used in Tanzania. Once built, the wall will be pushed to failure as force and displacement data is collected. Once recorded, the test data will be compared with the respective predictions made using code guidelines from ASCE 7 and TMS 402.

Procedure

Figure 1: Block Mix

To best emulate the concrete blocks used in Tanzania, the replica blocks were made with a mix ratio and method similar to what is used in Tanzania. The mix design used in Tanzania was determined by students who completed the first iteration of this project and who visited the country to observe fabrication and manufacturing processes. In Tanzania, the mix ratio used is typically based on volume rather than weight. For the replica blocks the ratios will be converted from the estimated volume to a weight to insure a consistent mix design since the volume of material required for the experiment is different than the volume produced for a batch of block. The concrete was mixed using the concrete mixer located in the CAED concrete yard at Cal Poly. The blocks were then made one at a time using a manual brick press supplied by the Architectural Engineering department. In addition to blocks, test cylinders were also collected from each mix. The cylinders were later tested in Cal Poly's Test Mark cylinder compressor to find the compressive strength of the concrete mix. Cylinders were tested 14, 23, 26, 30, 37, and 40 days after being cast in the moulds. The results of the compression tests can be seen in *Table 2*. After each block was made it was transferred to the curing room to cure for several weeks. The blocks were not perfectly symmetrical, but all were within a reasonable tolerance for an average dimension of $6^{1}/_{8}$" x $5^{1}/_{16}$" x $12^{1}/_{8}$". After 28 days, the blocks were assumed to be sufficiently cured and were used to construct two walls that were tested for out-of-plane strength.

Figure 2: Sand A Block

	Water	Cement	Fine Aggregate	Large Aggregate
Typical Tanzania Concrete Block Mix Ratio	1.24	1	12.2	N/A
Typical U.S. Concrete Block Mix Ratio (Approx. 3ksi)	0.53	1	2	3

Table 1: Comparison of Mixtures used in USA & Tanzania

There are several differences between the typical mixture of concrete used to make blocks in Tanzania versus what is commonly used in the USA as shown in *Table 1* above. The biggest differences are that large aggregate is not used and roughly six times more fine Aggregate (sand) are used in Tanzania compared to the USA.

Figure 3: Sand B Block

One additional factor that should be noted is that the concrete mixtures do not contain the same sand. During the period of time when the concrete blocks were being made the supply of sand was restocked. The restocked sand had a different color and a different texture than that of the sand used for the first several mixes. The first sand, used in mixes one through four,

will be referred to as Sand A, and the sand used in mixes five through seven will be referred to as Sand B. Sand A's mixture produced a dense light-grey colored block with little voids on its exterior. Sand B's mixture produced a block that contained multiple air voids on its exterior. Examples of a Sand A and a Sand B block can be seen in *Figures 2 and 3* respectively. Unfortunately, the change of sand was not anticipated, so no samples of Sand A were collected or closely observed to compare with Sand B. During the mixing process the sand used in the mix was documented. The sand was also documented for each cylinder in order to allow for comparison when testing, the results of the testing for each sand is shown in *Table 2*.

Two walls were built using two different block patterns. The first wall was built with the concrete blocks laying horizontally, long face down. It was three bricks wide and 12 courses high totaling 36 bricks and measuring $37^1/_8$ inches wide and $66^1/_8$ inches tall. The vertical reinforcement consisted of two vertical rebar spaced 12½ inches on center and the horizontal reinforcement was six horizontal rebar placed between every other block (shown in *Figure 4* on the right), all reinforcement was a #3 size rebar. This wall will be referred to as the Horizontally Orientated Block Wall (HBW). HBW was made with only blocks mixed with Sand A, therefore the compression strength used was determined from the average of Sand A's cylinders.

Figure 4: HBW and Reinforcement

The second wall was built with the concrete blocks laying vertical, short face down. It was 6 blocks wide and 6 courses high totaling 36 bricks measuring 33¼ inches wide and 75¾ inches tall. The reinforcement consisted of three horizontal rebars at every other block and two vertical rebars at 22½ inches on center(shown in *Figure 5* on the right) , all size #3 rebar. The available reinforcement was shorter than the height of the wall. So, the vertical rebar was spliced 27 inches in accordance with Section 6.1.6.1.1.1 of TMS 402. This wall will be referred to as the Vertically Orientated Block Wall (VBW). VBW was made almost entirely of blocks mixed with Sand B, therefore the compression strength used was determined from the average of Sand B's cylinders.

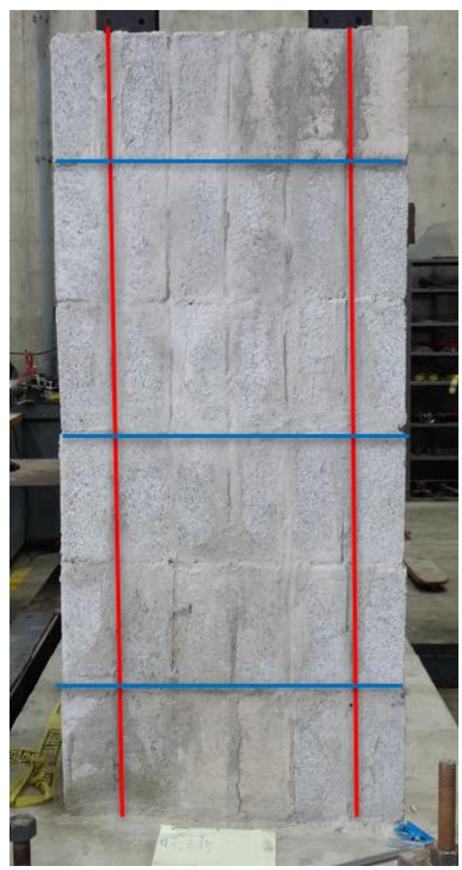

Figure 5: VBW and Reinforcement

A prediction for the flexural strength of each wall was made prior to testing based on the compression/cylinder test results. Once the mortar for the wall cured for 28-days, each wall was pushed to failure. Data for each wall was recorded over the duration of the tests and graphed. *Tables 2a and 2b* summarizes the predicted values for both walls. The calculations for these values can be found in the appendix. The final strength of each wall found during testing was compared with their respective predicted strengths on *Figures 11 ,12, and 13.*

Wall	Rho	Em (psi)	Cracking out-of-plane force (lbs)			Base cracking moment (lbs-")		
			Fy= 60ksi	Fy= 66ksi	Fy= 70ksi	Fy= 60ksi	Fy= 66ksi	Fy= 70ksi
Horizontal	0.00192	218070	78	95	117	5148	6275	7762
Vertical	0.00215	203400	112	146	189	8458	11070	14351

Table 2a: Summarization of Calculations

Wall	Out-of-plane failure force (lbs)			Base failure moment (lbs-")			Max drift		
	Fy= 60ksi	Fy= 66ksi	Fy= 70ksi	Fy= 60ksi	Fy= 66ksi	Fy= 70ksi	Fy= 60ksi	Fy= 66ksi	Fy= 70ksi
Horizontal	461	484	504	30473	32003	33307	1.82%	1.57%	1.32%
Vertical	355	366	373	26902	27724	28256	1.28%	1.01%	0.79%

Table 2b: Summarization of Calculations Continued

Testing Results

Cylinder Testing

Figure 6: Cylinder Before Test

Over the course of ten weeks, 12 cylinders were tested from seven different batches. Each batch consisted of 280lbs of sand, 23lbs of cement, and 35-40lbs of water. The variation in water occurred in order to reach a desired mix constancy. The final mix design was roughly one-part cement, twelve parts sand, and one- and one-half parts water. With such a high ratio of sand to cement and a low ratio of water to cement, the strength of this mix was expected to be rather low. For comparison, a mix with a ratio of 1:5:10 has an expected strength of 725psi [1].

Figure 7: Cylinder After Test

The testing for the cylinders took place in the concrete lab using the Olsen Test Mark machine. The tests occurred at roughly 14 days, 28 days, and 35 days. The average compressive strength at around 28 days was 259psi for Sand A and 226psi for Sand B. These values were determined to be the best to use since they were higher than the 40 day test results (the 40 day results should have been higher than the 28 day results) and most consistent data samples that were found. These values are highlighted in green in *Table 3*. *Table 3* also contains data collected from all cylinder testing for background information. The cylinders were very brittle, as one would expect from concrete, with little cracking occurring before the cylinders crumbled into pieces as the compressive strength of the concrete specimens was achieved.

Type/Time	PSI	Sand
14 day compresion	204	A
23 day compresion	218	B
23 day compresion	240	B
23 day compresion	220	B
26 day compresion	263	A
30 day compresion	313	A
30 day compresion	200	A
37 day compresion	201	B
37 day compresion	169	B
37 day compresion	209	B
40 day compresion	218	A
40 day compresion	140	A

Average Strength for Concrete with Sand A		
30 Day	40 Day	Both
259	179	219

Yellow data provided for background

Average Strength for Concrete with Sand B		
23 Day	37 Day	Both
226	193	218

Table 3: Cylinder Testing Results

<u>Wall Testing</u>

Figure 8: VBW (left) & HBW (right)

The two walls were constructed and tested for out-of-plane strength, since this is the critical loading for the wall configurations used in Tanzania. Each wall was pushed or loaded at its top. The pushing was applied using a hydraulic press. The set ups for each test specimen are shown in Figure 9 and Figure 10. For each test, the force being exerted on the wall and the corresponding horizontal deflection were recorded. In addition, crack formations were recorded for analysis and observations. Charts showing the force-displacement relationship for each test are shown in Figure 11 and Figure 13.

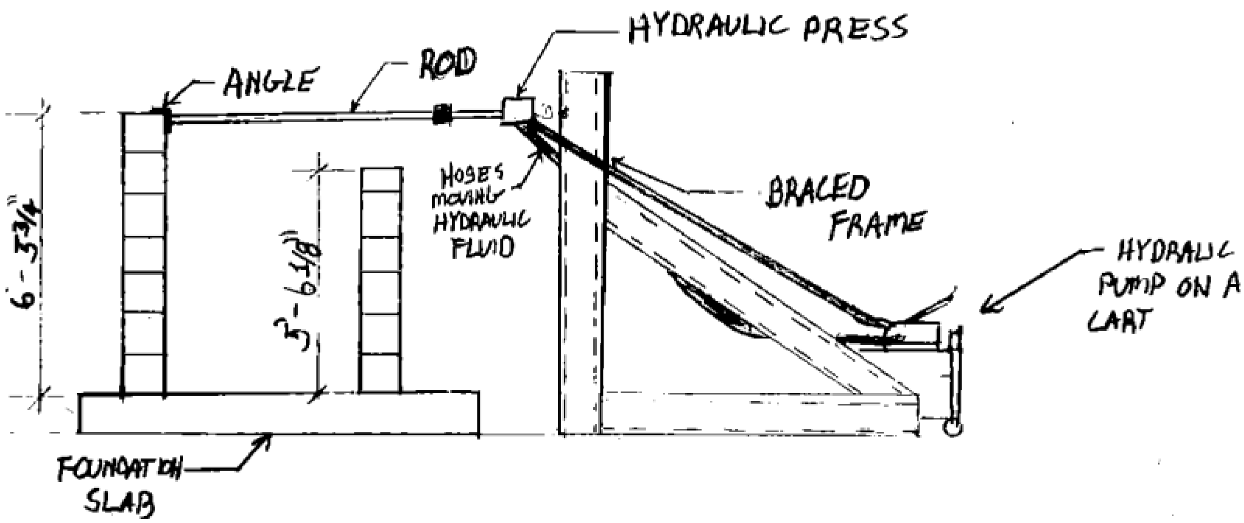

Figure 9: Schematic of Vertical Wall Testing

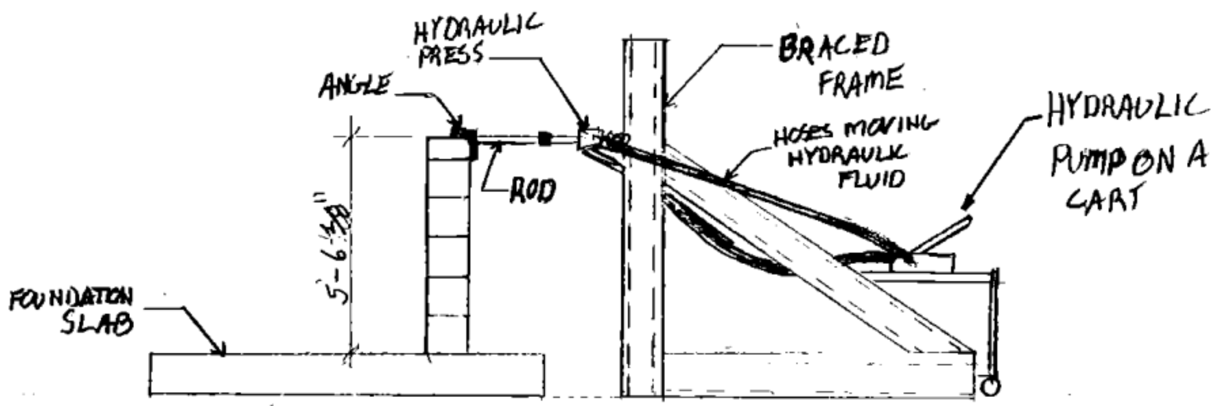

Figure 10: Schematic of Horizontal Wall Testing

Predictions

Using TMS 402 section 9.3.5, Wall One was predicted to fail at around 450lbs of force, or a base moment of 29.5 kip-in. Using the deflection equation for a cantilever and assuming cracked section properties, a lateral displacement of 1.1 inches was predicted for this amount of loading. Using TMS 402 section 9.3.5 as reference for Wall Two, it was predicted to fail at around 370lbs of force, or a base moment of 28 kip-in. Using the same procedure, a cantilever a displacement of 1.1 inches was predicted for this amount of loading.

Results

The Horizontally Oriented Block Wall failed at about 440 pounds of force, or a base moment of around 29 kip-in. It had a deflection of about 4.0 inches. The results of the testing along with the predicted values for the Horizontal Wall are shown in *Figure 11* below.

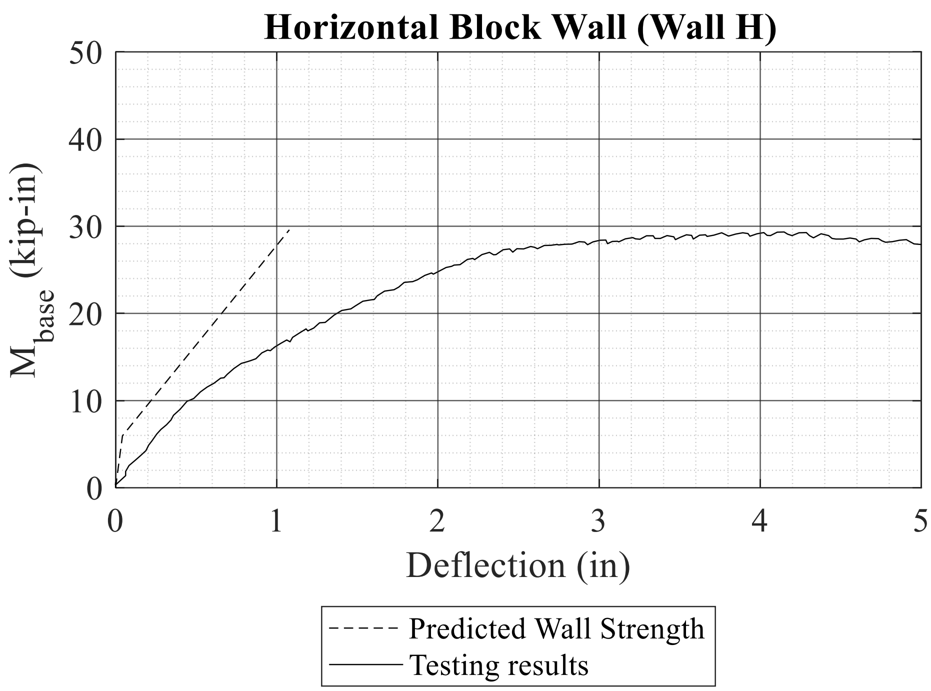

Figure 11: Horizontal Wall Prediction and Test Results

As evident from *Figure 11*, during the testing the wall started cracking much earlier than predicted. During the testing, this brittle behavior was easily observed; the bottom two courses of blocks started cracking along the mortar line almost immediately after starting the test. The second course from the bottom started to lift away from the bottom course as the test proceeded (depicted in *Figure 12* below). As the test progressed, the bottom course cracked and crumbled continuously, turning the bottom course of blocks into rubble rather than the block remaining solid and cementitious. From this behavior, it seemed as though the blocks were contributing little to the wall's stiffness and structural strength, instead the reinforcement was the main contributor of stiffness and strength to the wall.

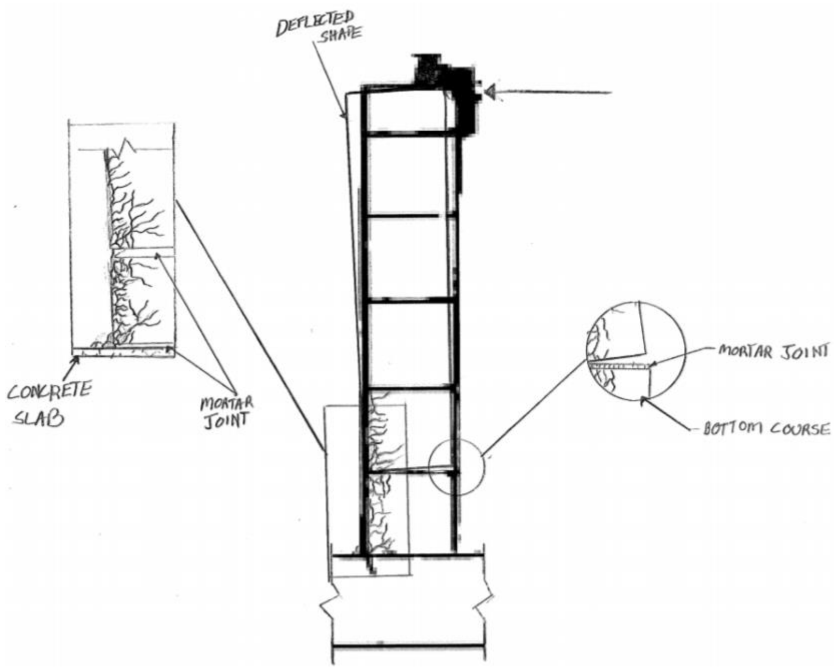

Figure 12: Horizontal Wall Deflected Shape

The Vertically Oriented Block Wall failed at about 525 pounds of force, or a base moment of approximately 40 kip-in. It had a deflection of about 2 inches. The results of the testing along with the predicted values for the Vertical Wall are shown in *Figure 13* below.

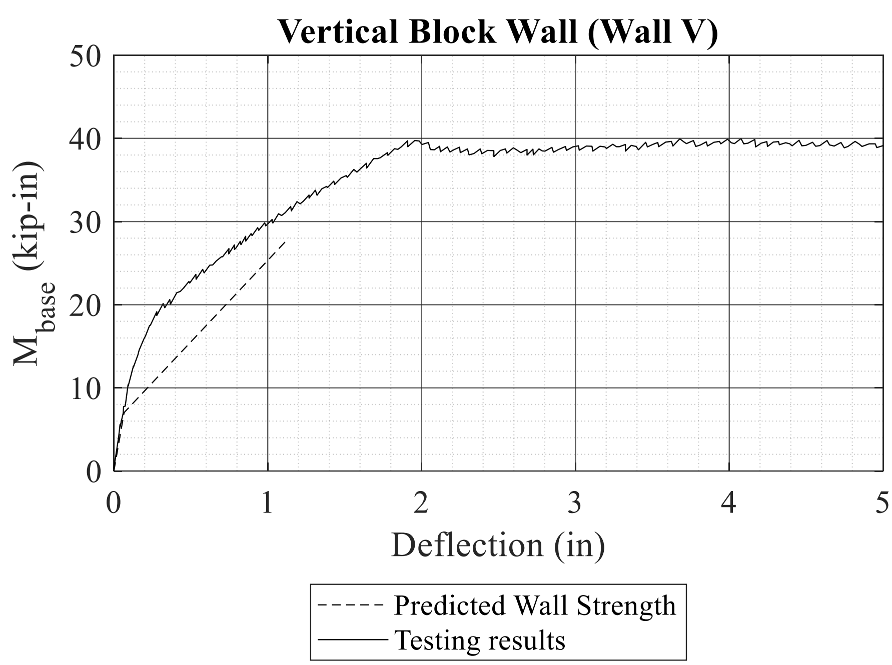

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Figure 13: Vertical Wall Prediction and Test Results

Unlike the Horizontal Wall, the Vertical Wall started cracking around the predicted force (as supported in *Figure 13*). As the blocks started to crack, the cracking occurred at the bottom two courses as illustrated in *Figure 14*. Most of the cracking occurred at the bottom two courses, however, cracking was observed at other courses as well. Before the bottom two courses completely failed, the bottom course started to separate from the concrete slab support (depicted in *Figure 14* below). As separation began, the blocks began to crumble in a brittle fashion at the points where they were still in contact with the concrete base. As the bottom course began to crumble, the deflection of the wall started to increase greatly (seen in *Figure 13* at 20 kip-in base moment). During this time, it was observed the blocks started to contribute less and less to the stiffness of the structure and most of the force was being taken by the reinforcement.

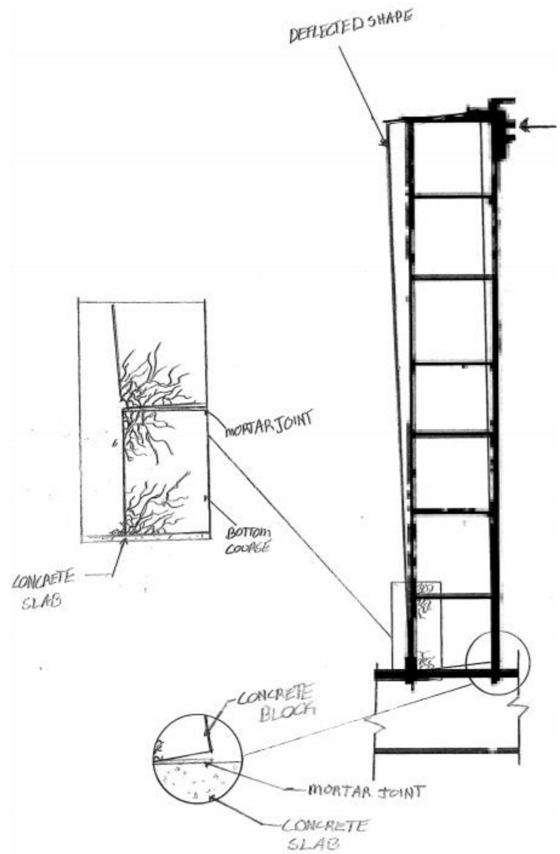


Figure 14: Vertical Wall Deflected Shape

When comparing the two walls, a few differences are observed. Both walls failed rather similarly, with both having their bottom courses fail brittlely and deflected more than anticipated. However, the vertical oriented wall failed at a higher force than anticipated while the horizontal oriented failed roughly at the predicted force. *Figure 15* shows both wall tests and the predictions all in one graph for comparison. The line curve for the HBW is less linear and similar to the curve one would anticipate from steel, suggesting that the steel reinforcement was the main resistance system of the wall and not the blocks. The testing curve for the VBW suggests a composite behavior from the blocks and steel reinforcement.

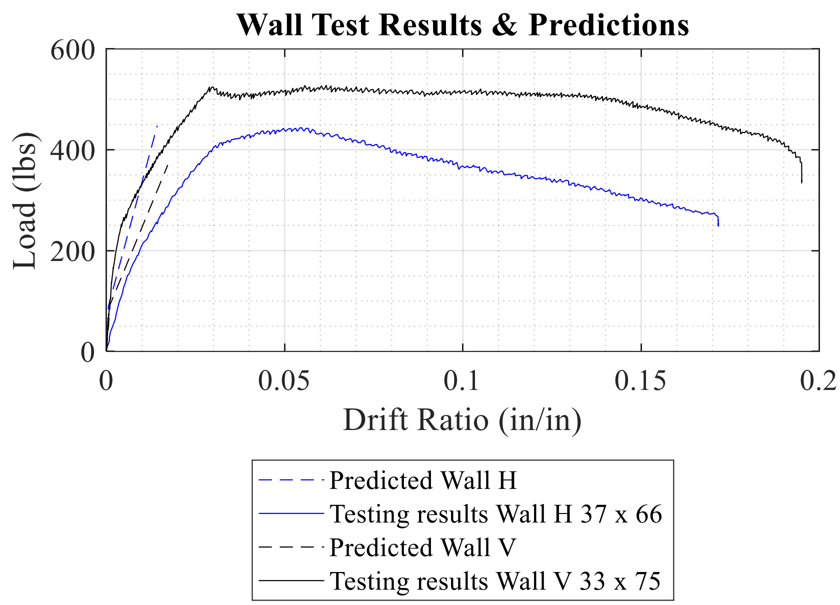


Figure 15: Wall Predictions Compared to Tests

Conclusion/Report

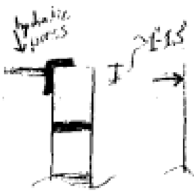
Both walls were not as stiff as was predicted when tested. One reason for this could be the fact that the concrete blocks were not as stiff as predicted. Another factor could be the ultimate strength of the reinforcement. For the predictions, the reinforcement was taken as 60ksi, however, most manufactured reinforcement yield strength is above the labeled strength, but it is common practice to use to use 60ksi when designing in order to be conservative. The nonlinear nature of the experimental curves is expected due to the concrete blocks cracking as well as the nonlinear behavior of yielding steel. However, this nonlinear behavior happened much earlier in the horizontal wall due to the wall starting to crack almost immediately. The experimental curves for both walls were not much like their respective predicted curves, suggesting that more work may need to be done on the prediction method and/or testing methods. Although, the predicted strength of the horizontal wall was fairly accurate to the final strength of the horizontal wall during testing, suggesting one may be able to make a rough prediction of a horizontal wall's strength. However, these curves were not close enough and the sample size too small to determine a Tanzanian CMU walls out-of-plane strength with much confidence and/or accuracy.

The testing data shows that the stiffness of the vertical wall was much greater than that of the horizontal wall as well as what was predicted for either wall. There are several possible reasons for this, the most notable are: less than accurate testing data of concrete blocks; two types of sand used in creating the blocks causing different behaviors from the blocks; faulty assumptions made on reinforcing rebars strength when making predictions; and the width of the walls. To help mitigate these variables future testing should place more focus on testing of the concrete blocks and/or cylinders of the mix. This will hopefully give higher accuracy for assumed block strength when predicting the wall strength. Testing should also be done on the reinforcement to find its actual yield strength instead of its design strength. In order to avoid multiple sand types future testers must coordinate with the technician in the concrete yard to see if new shipments will be delivered during the mixing stages of testing. With these improvements the hope is more variables can be eliminated and a more accurate method of predicting a walls out-of-plan strength and deflection can be made.

Appendix

Calculations

1/4



FBD

due to 1.5" only being < 3% of wall height, & the uncertainty of how the load was distributed, the location of the force will be taken @ the top of the walls

Wall HBW

$A_s = 2(.11^{\#}) = 0.22^{\#}$ $\quad d = \frac{6.16''}{2} = 3.08''$ $\quad h = 66.125''$

$b = 37.125''$ $\quad f_y = 60^{ksi} = 60000\,psi$

$P_u = \left(\frac{7.1^{\#}}{\pi(2'')^2 8''}\right) 37.125''(6.16'')\left(\frac{66.125''}{2}\right)$ (1/2 wall height for simplicity)

$P_u = 534^{\#}$

(1) $f_r = 100\,psi$ $\quad f'_m = 2423\,psi$ (from testing)

$M_n = \left(\frac{P_u}{\phi} + A_s f_y\right)\left(d - \frac{a}{2}\right)$ $\quad$ (2) $\phi = 0.6$

$a = \frac{A_s f_y + P_u/\phi}{.8 f'_m\, b} = \frac{(.22^{\#})6000psi + 534^{\#}/.6}{.8(242.3psi)(37.125'')} = 1.96''$

$M_n = \left(\frac{534^{\#}}{.6} + .22^{\#}\,6000psi\right)\left(3.08 - \frac{1.96''}{2}\right) = 2958^{\#''}$

$M_{cr} = S_{cr} f_r$ $\quad S_{cr} = I_{cr}/y = I_{cr}/d$

$I_{cr} = n\left(A_s + \frac{P_u}{f_y}\frac{t_{sp}}{2d}\right)(d-c)^2 + \frac{bc^3}{3}$

$n = \frac{E_s}{E_m} = \frac{29000000\,psi}{900(2423psi)} = 132.98$

$t_{sp} = 2d$ $\quad \therefore \frac{t_{sp}}{2d} = 1$
(since rebar is centered)

$C = \frac{A_s f_y + P_u}{.64 f'_m\, b} = \frac{.22^{\#}(6000psi) + 548^{\#}}{.64(242.3psi)(37.125'')} = 2.39''$

L-14

$$I_{cr} = 132.98\left(.22^{\#} + \frac{531^{\#}}{60000psi}\right)(3.08'' - 2.39'')^2 + \frac{(37.125'')(2.39'')^3}{3}$$

$$\Rightarrow I_{cr} = 183.43\,in^4$$

$$S_{cr} = \frac{183.43\,in^4}{3.08''} = 59.56\,in^3$$

$$M_{cr} = (59.56\,in^3)(100\,psi) = 5956^{\#''}$$

$$P_c = \frac{M_n}{h} = \frac{29589^{\#''}}{(66.125'')} = 447.5^{\#}$$

$$P_{cr} = \frac{M_{cr}}{h} = \frac{5956^{\#''}}{(66.125'')} = 90.1^{\#}$$

$$\Delta_c = \frac{P\ell^3}{3EI} = \frac{P_c\,\ell^3}{3E_m\left(\frac{bh^3}{12}\right)} = \frac{(447.5^{\#})(66.125'')^3}{(3)(900)(242.9\,psi)\left(\frac{66.16''(12.18'')^3}{12}\right)} = 0.213''$$

$$\Delta_{cr} = \frac{P_{cr}}{3E_m}\frac{\ell^3}{I_{cr}} = \frac{(90.1^{\#})(66.125'')^3}{(3)(218070\,psi)\,183.43\,in^4} = 0.217''$$

$$K_1 = \frac{P_c}{\Delta_c} = \frac{447.5^{\#}}{0.213''} = 2100.94\ ^{\#}/_{''}$$

$$K_2 = \frac{P_{cr}}{\Delta_{cr}} = \frac{90.1^{\#}}{.217''} = 415.21\ ^{\#}/_{''}$$

$$\Delta = \frac{P_c\,\ell^3}{3E_m\,I_{cr}} = \frac{447.5^{\#}(66.125'')^3}{(3)(218070\,psi)(183.43\,in^4)} = 1.08''$$

3/4

Wall 2 (N/a 2)

$d = \frac{6.16''}{2} = 3.08''$

$A_s = 2(.11^{\#}) = .22^{\#}$

$b = 33.25''$ (~1.218' / block)

$f_y = 60^{ksi} = 60000psi$

$h = 75.75''$

$P_u = \left(\frac{7.1^{\#}}{\pi (2'')^2 (8'')}\right)(33.25'')(6.16'')\left(\frac{75.75''}{2}\right)^{*}$

* ½ of wall height used for simplicity

$P_u \approx 548^{\#}$

① $f_r = 100psi$

$f'_m = 242.3psi$

① TMS402 T.9.1.9.2

$M_n = \left(\frac{P_u}{\phi} + A_s f_y\right)\left(d - \frac{a}{2}\right)$

② $\phi = 0.6$

② §9.1.4.3

$a = \frac{A_s f_y + \frac{P_u}{\phi}}{.8 f'_m b} = \frac{(.22^{\#})(60000psi) + \frac{548^{\#}}{.6}}{.8(242.3psi)(33.25'')} = 2.19''$

$M_n = \left(\frac{548^{\#}}{.6} + (.22^{\#})60000psi\right)\left(3.08'' - \frac{2.19''}{2}\right) = 28015^{\#''}$

$M_{cr} = S_{cr} f_r$

$S_{cr} = I_{cr}/y = I_{cr}/d$

$I_{cr} = n\left[A_s + \frac{P_u}{f_y}\frac{t_{sp}}{2d}\right](d-c)^2 + \frac{bc^3}{3}$

$y = 3.08''$

$t_{sp} = 2d \quad \therefore \frac{t_{sp}}{2d} = 1$

$c = \frac{A_s f_y + P_u}{.64 f'_m b} = \frac{(.22^{\#})(60000psi) + 548^{\#}}{.64(242.3psi)33.25} = 2.67''$

$n = \frac{E_s}{E_m}$

$E_m = 900 f'_m = 218070psi$

$n = \frac{29000000psi}{218070psi} = 132.98$

$I_{cr} = 132.98\left[.22^{\#} + \frac{548^{\#}}{60000psi}\right](3.08 - 2.67'')^2 + \frac{(33.25'')(2.67'')^3}{3}$

$\Rightarrow I_{cr} = 216.1 in^4$

9/4

$$S_{cr} = \frac{216.1\,in^4}{3.08''} = 70.2\,in^3$$

$$m_{cr} = (70.2\,in^3)(100\,psi) = 7020\#''$$

$$P_c = \frac{m_n}{h} = \frac{28015\#''}{75.75''} = 369.8\#$$

$$P_{cr} = \frac{m_{cr}}{h} = \frac{7020\#''}{75.75''} = 92.7\#$$

$$\Delta_c = \frac{P l^3}{3EI} = \frac{P_c l^3}{3E_m\left(\frac{bh^3}{12}\right)} = \frac{(369.8\#)(75.75'')^3}{(3)(218079\,psi)\frac{(6.16'')(12.5'')^3}{12}} = 0.265''$$

$$\Delta_{cr} = \frac{(P_{cr})\,l^3}{3E_m I_{cr}} = \frac{(92.7\#)(75.75'')^3}{(3)(218090\,psi)\,216.1\,in^4} = 0.285''$$

$$K_1 = \frac{P_c}{\Delta_c} = \frac{369.8\#}{0.265\#} = 1395.5\,\#/in$$

$$K_2 = \frac{P_{cr}}{\Delta_{cr}} = \frac{92.7\#}{1.42''} = 65.3\,\#/in$$

$$\Delta = \frac{P_c l^3}{3E_m(I_{cr})} = \frac{369.8\#(75.75'')^3}{(3)(218079\,psi)(216.1\,in^4)} = 1.14''$$

Additional graphs

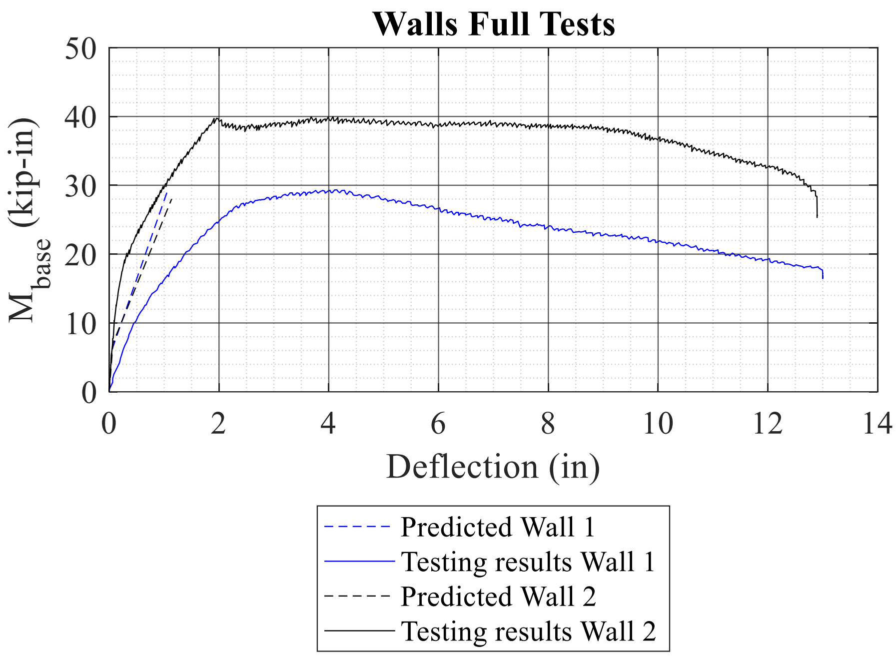


Figure 14: Testing fill failure

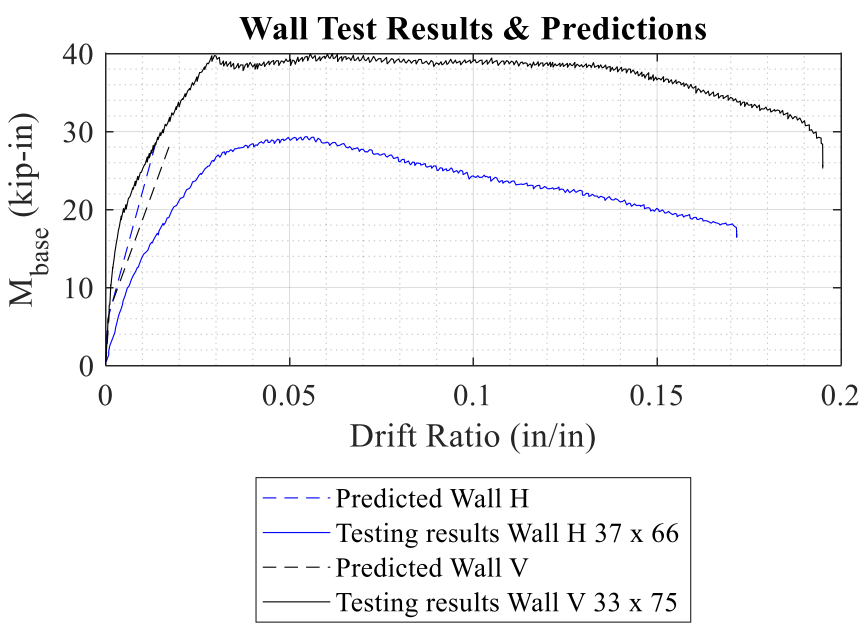


Figure 15: Wall's base moments compared to their drift ratio

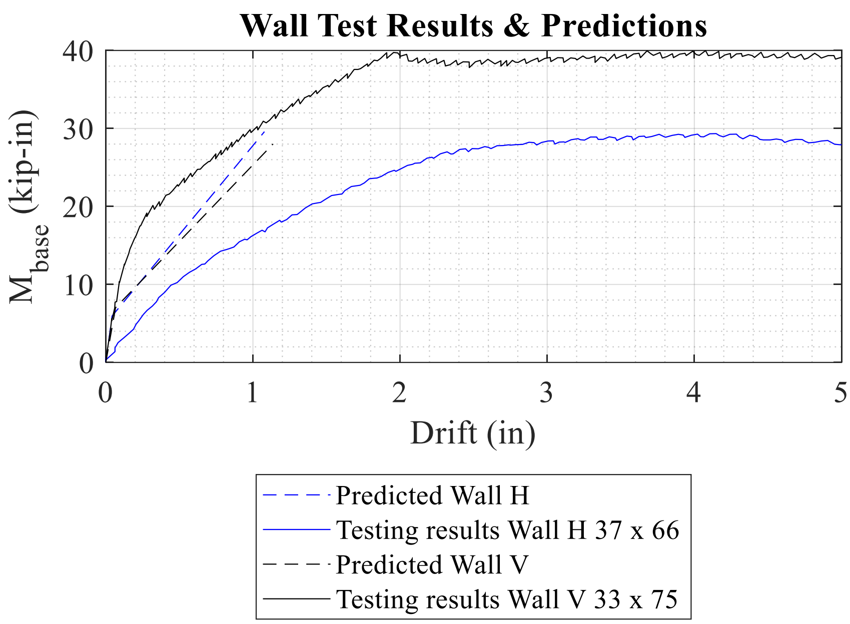


Figure 16: Wall base moment compared to top of wall displacement

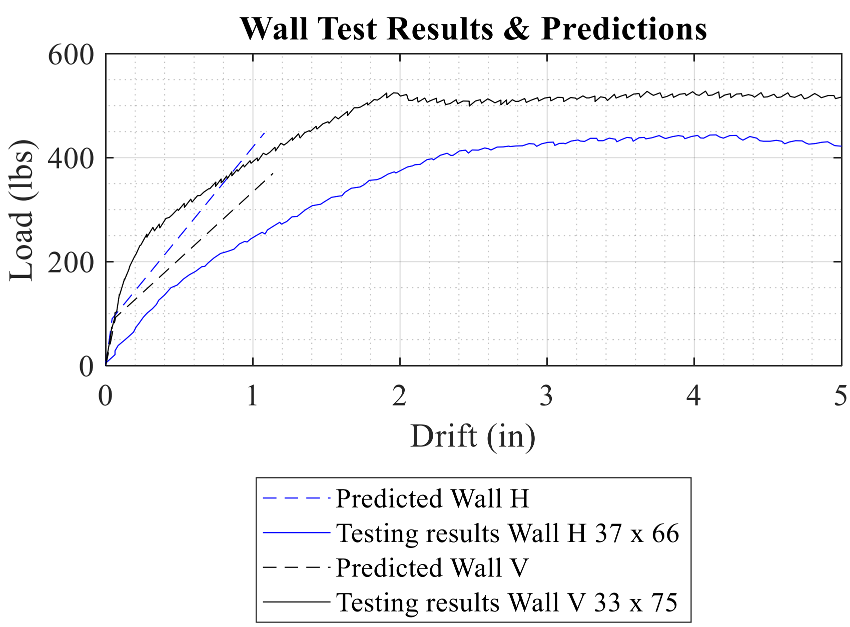


Figure 17: Wall's point load compared to their drift ratio

Additional Photos

Figure 18: Manual brick compressor

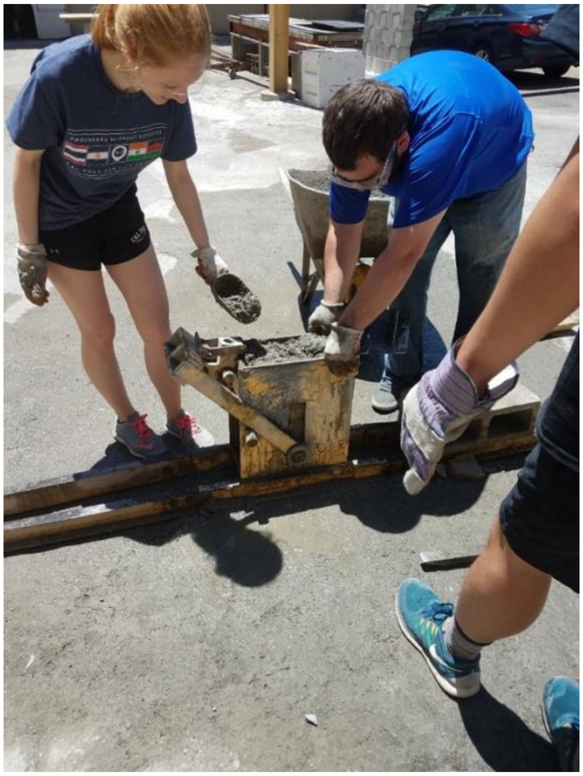


Figure 19: Filling brick compressor

Figure 20: Curing room for concrete blocks

Figure 21: Example of hand mixing concrete in Tanzania

Figure 22: Example of Tanzanian construction

Figure 23: Tanzanian Construction site

Batching: https://www.aboutcivil.org/batching-mixing-placing-compaction-of-concrete.html

[1]: https://theconstructor.org/concrete/types-of-concrete-mix-design/5984/