

Senior Project: Masonry Core Testing

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Scope

Background

The 1933 Long Beach Earthquake and 1971 San Fernando Earthquake changed the construction of school and hospital buildings. The Field Act was a result of the catastrophic damage in 1933, in which school buildings were to be inspected and engineered by a regulatory agency- The Department of the State Architect (DSA). Similarly, the Alfred E. Alquist Hospital Facilities Seismic Safety Act prompted hospitals to have the same regulations. This act is enforced by the Office of Statewide Health and Planning Department (OSHDP). Included in these regulations is Masonry Core testing per California Building Code (CBC) 2105A.4.

Masonry core testing was adopted as a regulatory procedure to ensure masonry walls on school and hospital buildings were constructed properly. The code inspects the quality of bond between the CMU and grout by extracting core samples from erected masonry walls and testing the cores after 28 days. Using an accepted testing apparatus, “the average unit shear value for each pair of cores... shall not be less than $2.5\sqrt{f'm}$ ”. The cores shall be extracted per CBC 2105.4. The examination and results for the cores must be reported even when the core specimens fail the test. A failure would be defined as the CMU face shell falling off during testing or a shear value of less than $2.5\sqrt{f'm}$. Failing this test causes many problems for the engineer.

Most engineers regulate masonry construction with admixtures to ensure a bond. Rarely but very possibly, a mistake in the field can cause a delamination between the grout and masonry. Because of the tight regulations DSA and OSHPD requires, they have adopted a “No Bond, No Go” statement for masonry walls that fail core testing. “No Bond, No Go” strictly states that the engineer may not fully consider the designed capacity for a wall with a poor grout to CMU bond. This leaves a few solutions for the engineer:

1. Re-calculate the wall ignoring the face shells using concrete strength design from the grout core and rebar only – only works for walls that are low stressed and not too tall.
2. Ask for additional cores at high stress areas to see if the problem exists there. If not, re-calculate capacity at low stress areas per 1 above, and ensure it can take design loads.
3. Reason with DSA and OSHPD – not likely
4. Reinforce the wall with steel – an expensive approach and may infringe on interior space

Purpose

Because of this “No Bond, No Go” statement, engineers must deal with costly and time consuming solutions. From several sources, engineers have convinced themselves that mechanical interlock of the grout and webs is enough to account for the delamination- however this is not enough to change DSA and OSHPD’s stance. Doing so would require testing on a masonry wall with a forced delamination between the grout and CMU to prove a reduction in strength is negligible. With that said, this experiment is designed to provide testing into this research issue from the Cal Poly Testing Lab. Hopefully this research may benefit structural engineers in the future.

Design

Construct two walls; one wall with bonded grout (Controlled Wall) and one without bonded grout (Failure Wall) and test both walls for out of plane load. To force a bond failure, provide small scale testing to determine a delaminating agent for the failure wall. To ensure the delaminating agent worked, core the walls per CBC 2105A.4. Additionally, construct a new testing slab for the Failure Wall. The design of this experiment was influenced by different structural engineering organizations- DSA, OSHPD, and the Concrete Masonry Association of California-Nevada (CMACN). Much of the advice considered was used to narrow the scope of this project. Most importantly, DSA would require out-of-plane testing to consider a critical load to define shear transfer between the CMU and grout. Non-destructive testing was a factor we would have liked to consider but did not have proper testing facilities in San Luis Obispo. We concluded the scope of this project would be to determine if a grouted CMU wall, without a positive bond, provides the out-of-plane capacity as designed.

Hypothesis

There will be a minimal difference in results (force and deformation) between the two walls. The masonry core test only considers the cohesion between the grout and CMU face shell. It does not consider the mechanical interlock of the webs and grout, tapering of the masonry, and aggregate interlock in full scale application. We believe these factors are enough to create a composite action in which the wall will act as one unit.

Process

Foundation Construction

Prior to construction, the Failure Wall needed a new testing slab in High Bay. The existing testing slab would be used for the control wall. This way, we can construct and test both walls simultaneously. The dimensions of the new slab was 9 feet by 4.5 feet and 1 foot thick. It was reinforced with no. 4 longitudinal rebar at 11" o.c and no. 6 latitudinal rebar at 10" o.c, top and bottom. 1.5-inch anchor bolts at 3 feet o.c was considered in the form work. These anchor bolts would be bolted to the High Bay Lab floor to prevent uplift. Reinforcing for the openings were also considered. Hooks were designed for mobility of the foundation to be lifted with the crane. See Appendix 1 for plans and sections of the slab.



Figure 1: Tying rebar cages into the slab formwork

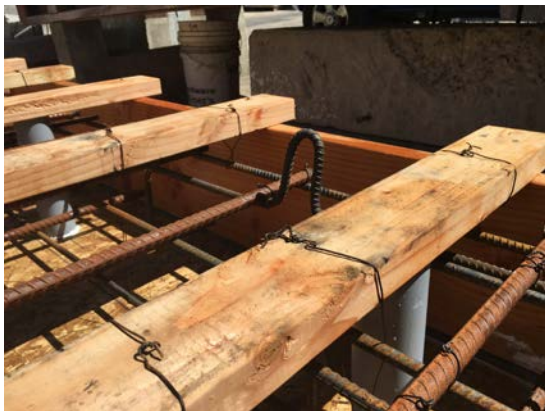


Figure 2: Hooks designed for lifting



Figure 3: Formwork and Reinforcing



Figure 4: Pouring concrete from CalPortland

Due to the short timeline, we needed the foundation to be lifted and bolted onto the High Bay Floors four days after the concrete is poured. For this reason, the reinforcement of the foundation was solely based on the slab's ability to carry its self-weight at 50% strength. CalPortland generously donated 1.5 cubic yards of concrete and AirVol block donated the reinforcement.

Small Scale Testing

The importance of this experiment is to test a forced delaminated grout to CMU wall. To ensure this delamination, several materials were tested. We discussed different techniques with Kurt Siggard from the CMAA. He highlighted the importance of retaining the same water ratio; therefore, it would be idea to use a water retaining agent. With this, we decided to try acrylic paint, Thompson's Water Seal, candle wax, and paper towel. To do this, we coated the inside face of CMU with the specified agent. Then, we grouted the cells and let cure for 3 days. Finally, it was cut with a water saw to observe the quality of the bond.

From the first tests, the acrylic paint gave the best result such that one face shell fell off. This was tested by being able to pull the face shell by hand strength. No other face shells fell off the other specimens; however, the Thompson's Water Seal and the paper towel showed visible separation between the grout and the CMU. The candle wax was ineffective. With these results, we decided to do a second pass with 2 layers of paper towel and Thompson's Water Seal on acrylic paint. Two layers of paper towel would give a thicker separation and Thompson's Water Seal would give an extra water sealable coat on the acrylic paint.



Figure 9: (2) Paper Towels

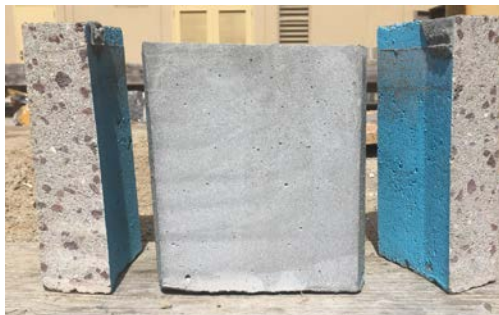


Figure 10: Thompson's Water Seal and Acrylic Paint

From figure 9 and 10, both tests were successful such that the face shells fell from both samples. The determining factor of what agent was used was based on constructability and application. First, the Thompson's and Acrylic paint was the cheapest and easiest to apply on the inner face shells. Secondly, knowing we would have to grout the cells, we needed a delaminating agent that would not be affected by grouting. The paper towel had a greater chance of falling off during grouting and was difficult to apply. Therefore, Thompson's Water Seal and acrylic paint was chosen as the delaminating agent.

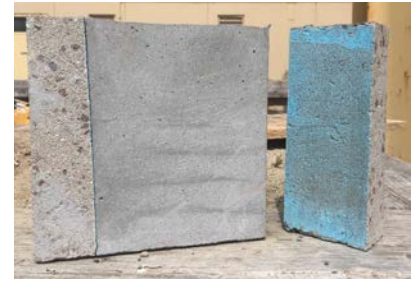


Figure 5: Acrylic Paint

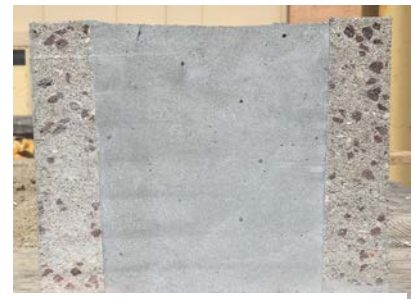


Figure 6: Thompson's Water Seal



Figure 7: Candle Wax



Figure 8: Paper Towel

Wall Construction

Fortunately, we had the opportunity to have two masons construct the two walls for this experiment. They were brought onto the project by John Chrysler from the Masonry Institute of America. The walls were built on April 27, 2017. The dimensions of the walls were 8 feet by 7.5 feet with 10-inch masonry block. No. 4 vertical reinforcement was laid at 18" o.c. and no. 4 horizontal reinforcement was laid at 32" o.c. We designed reinforcement to code minimums. However, we overdesigned the steel to ensure the CMU didn't crack before the entire wall was engaged. This way, we can observe a flexural response of the wall. Also, we wanted to model the wall assuming it would take load similarly to a typical school or hospital building. See Appendix 2 for wall section and elevation.

The wall was constructed to have pinned connections top and bottom. Therefore, we prepared the slabs with epoxied no. 4 dowels at 18" o.c. and embedded anchor bolts in the finished grout at roughly 16" o.c. along the wall.

No coating was applied to the inside faces of the controlled wall concrete masonry units. Each CMU block of the failure wall was coated with acrylic paint and Thompson's water seal three days before construction to allow the agents to dry completely. No specific brand of acrylic paint was used. The only requirement was that the acrylic paint was water based so the paint adheres to the CMU.



Figure 14: Buckets were used for grouting method

Type S mortar was used in construction and donated by AirVol Block. The walls were grouted 3 days after laying the blocks. To avoid cleanouts, we grouted in 4' lifts. Grouting proportions were 1 part gravel, 3 parts sand, 1 part cement and mixed to an 10" slump. Grouting materials were also donated by AirVol block. The wall cured for 17 days before coring.



Figure 11: Prepared block and epoxied dowels.



Figure 12: Anchor bolts embedded into grout.

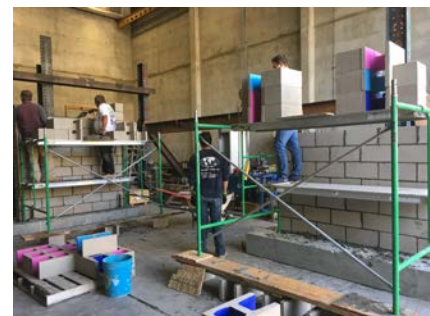
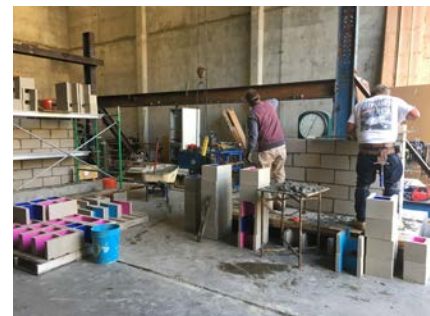


Figure 13: Wall Construction

Core Testing

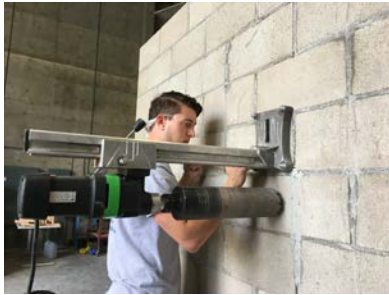


Figure 15: Mounted coring drill

Core testing will validate the efficiency of the delaminating agent and ensures a failure so the experiment may proceed as designed. Coring was performed per CBC 2105A.4. The holes were re-grouted with the same grouting mix during construction. Using a coring rig lent by Kurt Siggard, the drill was mounted with Hilti expansion anchors at the same locations in both walls. This was to maintain control of any differences between the two walls – aside from the grout to CMU bond.

The results were as planned. The core specimen from the control wall was intact and the specimen from the failure wall was not. In the process of extracting the core from the failure wall, the face shell fell off into the coring hole. As defined earlier, this is an automatic failure of the test.



Figure 16: Failed core test



Figure 17: Controlled wall core specimen



Figure 18: Grout to CMU bond

Figure 17 shows the intact core specimen from the controlled wall. Figure 18 shows a visible cohesion of the grout into the CMU block.

Figure 20 shows the failed core specimen of the failure wall. Figure 19 shows an obvious separation between the grout and the CMU. The pink acrylic paint is the visible barrier proving the efficiency of the delaminating agent.



Figure 19: Fallen face shell



Figure 20: Failure wall core specimen

The code requires a proper testing apparatus to be used when testing the shear value of the bond. For this experiment, we used a testing apparatus constructed by a previous senior project. The apparatus was designed for a 4" core specimen – acceptable for the 2016 CBC. Using the Tinius Olsen universal testing machine, we mounted the testing apparatus. The cores were tested roughly 40 days after grouting.



Figure 21: Testing apparatus



Figure 21A: Tinius Olsen Universal Testing Machine

Core Test Results				
Core	Control		Failure	
Diameter (in)	3.6875		3.6875	
Length (in)	9.625		9.625	
Shear Bond Strength(psi)	Inside	Outside	Inside	Outside
Load	4500	4750	150	X
Shear strength (psi)	421	445	14	N/A
Specified Strength (psi)	112	112	112	112
Pass/Fail	Pass	Pass	Fail	Fail

Table 1: Core Testing Results

As stated in the code, the average of the shear values of each end of the core must be no less than $2.5\sqrt{f'_m}$. The CMU blocks were tested at AirVol Block to have an f'_m of 2000 psi. Therefore, the minimum shear value must be 112 psi. From Table 1, we can conclude the control wall passed the masonry core test. On the other hand, the failure wall failed the core test by having a shear value less than 112 psi and a fallen face shell during extraction. With these results, we confirmed the delamination of the failure wall and the positive bond in the controlled wall.

Grout Testing



Figure 22: Grout sample compression test

In the curing process, the CMU absorbs water from the grout. There were raised concerns of the delaminating agent interfering with the hydration process of the grout due to the water retardant effects of the Thompson's Water Seal. Therefore, this test was designed to insure the delamination agent did not affect the strength of the grout.

A CMU block was filled entirely with grout to duplicate the curing conditions. A total of 12 samples were poured from one batch of grout - 6 control and 6 failure samples. After 28 days, rectangular samples were cut from the grout and compression tested using the Tinius Olsen Universal Testing Machine. Table 2 displays the compression test results.



Figure 23: Omitted sample

Grout Samples				
	Sample	Dimensions (in)	Load (lbs)	Comp. Stress (Psi)
Control	1	3x3	32900	3656
	2	3x3 1/8	33300	3552
	3	3x3	33000	3667
	4	3x3	29300	3256
	5	3x3	30500	3389
	6	3x2 7/8	26650	3090
Painted	1	3x3	32600	3622
	2	3x3	32500	3611
	3	3x3	28500	3167
	4	3x2 7/8	30200	3501
	** 5	2 7/8x2 7/8	21100	2553
	6	3x3	29200	3244

** Exclude Sample; force applied at angle, plate shifted during loading.

Table 2: Grout Sample Results

The average grout strength for both the failure samples and the control samples was roughly 3400 psi. One failure sample was omitted. During testing, the top plate shifted applying load at an angle causing spalling. Therefore, the entire sample was not properly engaged by the compression device.

The results of this test showed less than a half of a percent difference, per Table 3, between the failure samples and control samples. In conclusion, the delamination agent did not affect the hydration process of the grout.

Sample Comparison		
Control Average	3435	psi
Painted Average	3429	psi
Percent diff.	0.2	%

Table 3: Sample Comparisons

Top Bracing

Before we can proceed to testing, we created a pinned connection at the top of the wall. The anchor bolts embedded at the top of the wall were engaged to produce a connection similar to a wall fully braced by a diaphragm. We used a C12x20.7 faced down to hug the top of the wall and engage the bolts. 3-inch square tubes were bolted at each end of the channel and clamped to the wide-flange column approximately 6-feet away from the wall. The tubes were purposely placed at each end to reduce any possible torsion effects from testing. To save material and time, the bracing was constructed to fit both walls.

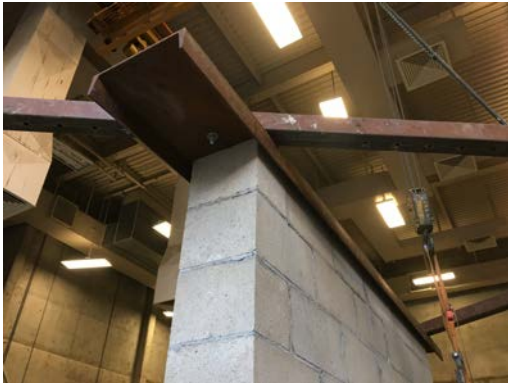


Figure 24: Top bracing



Figure 25: Channel engaging top anchor bolt

Out-of-plane Testing and Results

This experiment focuses on the deformation and force applied to the wall. The load applied for testing would be concentrated at the center of the wall and distributed with a previously constructed H-frame. This was the closest model we could achieve for a distributed out-of-plane force. A hydraulic ram with a pushing capacity of 50,000 lbs was used for this testing. A load cell and deformation gauge was attached to record results and linked to a computer analysis program. The results were recorded every second. Of the recorded results, we compared the maximum load and the maximum displacement. We determined the end of the test would be when the load applied would no longer increase. The calculated the capacity of the control wall was roughly 10,000 lbs, and the failure wall was 7,000 lbs per code design equations.



Figure 26: Typical testing configuration



Figure 27: Ram and load cell

The results of the wall test showed that the walls could withstand roughly the same load. The maximum load of both walls was within 10%, showing a significant interaction without a positive bond between the grout and CMU. The maximum displacement of the failure wall was nearly double that of the control wall under nearly the same load. Table 4 summarizes the results of the test. Though the maximum capacity of the wall was met, the wall continued to deform.

Visible observation from a recorded video showed a movement in the deformation of the walls.

Wall Test Max Load		
	Load (lbs)	Displacement (in)
Control Wall	23336	0.76
Failure Wall	21384	2.63

Wall Test Max Displacement		
	Load (lbs)	Displacement (in)
Control Wall	21862	1.17
Failure Wall	21384	2.63

Table 4: Out-of-plane results

Demolition Observations

After testing, we also observed the walls performance during demolition. Originally this was not an intended process for this experiment; however, it gave us promising results. The walls were pulled down and broken into 4 pieces. Two chains were hooked on the inner anchor bolts at the top of the wall, and pulled with a forklift.

The control wall displayed a strong bond between grout and CMU even given the aggressive nature of the demolition process (Figure 29C). It was difficult to break into 4 pieces by jack hammer. But, the debris, both large and small, clearly remained intact (Figure 29B). No face shell came off easily. It was impossible to break any piece off the controlled wall without the use of a jackhammer.

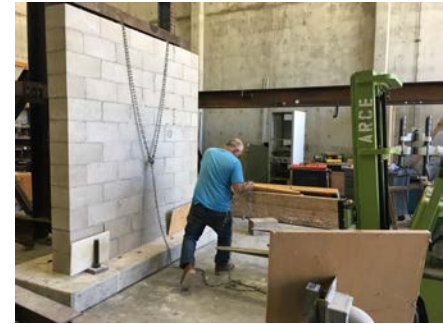


Figure 28: Demolition set-up



Figure 29A: Controlled wall demolition



Figure 29B



Figure 29C

When the failure wall was taken down, it was clear the grout had not adhered. The face shells broke off in large chunks all over the wall (Figure 30D). Under further demolition stresses, an entire corner of the wall broke off (Figure 30C). This would not have occurred had there been a proper grout bond. The grout was easily exposed but the intact webs proved some mechanical interlock (Figure 30B). A sledge hammer could easily break a face shell on the failure wall. However, the jackhammer was needed when trying to break into the grout.



Figure 30A: Failure wall demolition



Figure 30B



Figure 30C



Figure 30D

In conclusion, both walls performed as a single unit when being taken down. There was enough interlock for the failure wall to work in composite action. However, the damage and debris of the failure wall was much more than the controlled wall. There's no doubt this can cause a life safety hazard when performing under seismic loads or torsion. This creates a further question of the durability of the walls in cyclic loading.

Conclusions

Analysis

To address our hypothesis as stated on page 3, we can conclude the failure wall could act in composite action. We can confirm the mechanical interlock of the webs and grout and tapering of the masonry allowed composite effects. The results from the out-of-plane testing and demolition of the wall proved the ability of the wall to perform as a unit. However, we cannot conclude the performance of the wall to be acceptable past failure. The corner of the wall that fell off in Figure 30 was proof that the wall may not be durable enough for life safety. While it's common for cracking to occur, the CMU to grout bond controls a reduction in section under cracking. Without the bond, there's no way to ensure the wall will act in its fully designed section. Had there been a positive bond in the failure wall, the corner section would remain intact with the entire wall. Figure 31 highlights obvious area where the bond should have formed.



Figure 31: Delamination of corner section

Possible Errors



Figure 32: Failure wall base

The foundation that the failure wall was built on was not completely roughened at the base of the wall. During the demolition process of the failure wall, it was apparent the foundation was too smooth for stronger cohesion. There could have been a stronger bond at the base like that of the other foundation. The other foundation had a cross hatch on the slab to allow the mortar and grout to interlock. Figure 29C shows the remaining two block layers still attached to the slab. Figure 31 shows the base of the failure wall completely detached from the slab. The smooth surface of the grout and mortar can be observed.

In a video recording of the failure wall test, it was revealed the deformation was not entirely in the wall. Visual observation in the video displayed deformation is both the wide flange and the wall. Therefore, the wide flange no longer served as an anchor point. Instead, the ram was exerting force onto both the wall and wide flange. We can confirm that both the wall and the wide flange experienced the same loading- this does not affect the loading results.

Observations

Some of the most telling results came from processes that we never intended to give us results.

- 1) During the small-scale testing, the first indication we received of a working delaminating agent was tossing a cut off piece of the prisms into the recycling pile. We noticed the slight force of impact caused the grout to be ejected from the face shell as a solid piece (Figure 33). Although this was not purposeful in considering a proper failure mechanism, we discovered it was a worthy test to influence our choice of the delamination agent.
- 2) The demolition of the failure wall allowed us to discover a couple of concerns with the performance of failure. This changed our perception of the assumed unitary performance that we witnessed from the out of plane test.



Figure 33: “Throw Test”

It's important to note this is the worst-case scenario of a wall that fails masonry core testing. The failure wall was intended to have complete delamination of the grout and CMU. In practical construction, delamination may occur on only certain parts of the wall.

Further Research

Our experiment showed promising results, but also raised further questions about how delaminated grout affects the strength, but more importantly the durability of a delaminated CMU wall. These tests should serve as a proof of concept of forcing a bond failure. Further research must be done to fully understand the consequences of such a failure such as:

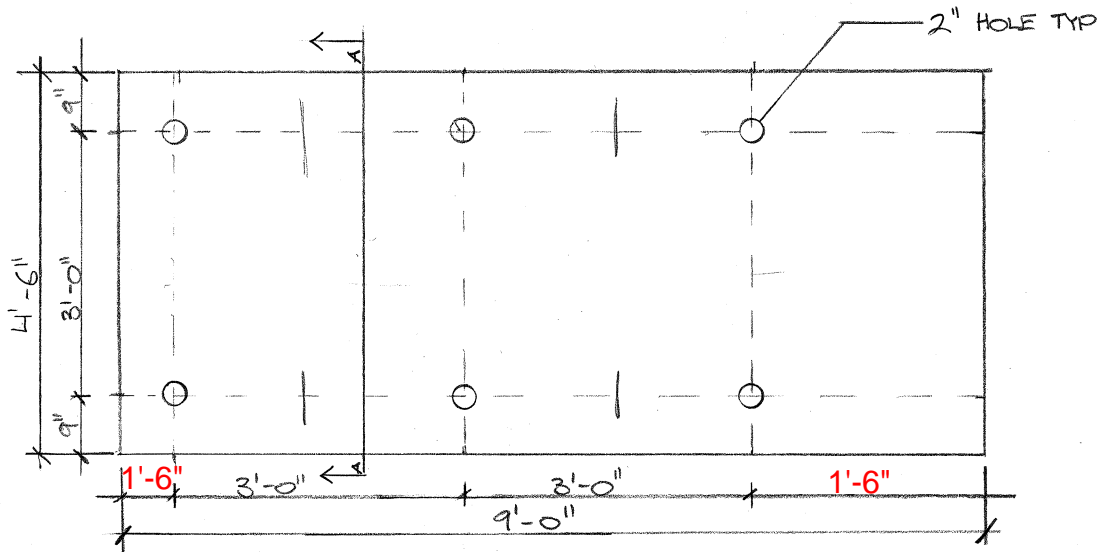
- 1) Smaller scale prism testing to observe the behavior of the interlock under concentrated loads (torsion, out-of-plane, impact, etc.) For example, CMU prisms constructed of 5 or 6 blocks tall and 1 or 2 blocks wide with a small amount of reinforcement- likely a number 3 bar. This would allow the minimum needed interaction between grout and CMU. The smaller loads required to test these samples are much more practical to produce, and are less likely to cause equipment malfunctions.
- 2) The behavior of a failure wall under earthquake loading and considering cracked sections.
- 3) Use of non-destructive testing methods to examine positive bonding in a purposefully delaminated wall and conclude an acceptance criteria.

Closing Remarks

We were very pleased with the results from this experiment. Executing the experiment revealed more than what we planned to observe. Looking back, this was a very big project for one quarter. Luckily, we planned and designed the experiment fall and winter quarter. We took that time to contact our connections from DSA, CMAACN, ZFA Structural Engineering, and Barrish Pelham Consulting Engineers for advice on the scope. Also, notifying Ray Ward, the ARCE Lab Technician, of this project early on helped prepare him for construction and testing soon to happen in High Bay Lab. We are very grateful to have materials and time donated to the project. Much communication and coordination happened prior to construction in the Spring time. We applied structural design, construction management, and construction techniques learned throughout our ARCE curriculum. Without realizing it, we worked with every material we studied – masonry, concrete, timber, and steel. We had to deal with designing and constructing connections as well. Of the problems we faced, we realized much can go wrong during construction and field fixes must be improvised but adequate. Luckily under the supervision of Ray Ward, we were taught the skills necessary over the past quarter to overcome these challenges. In summary, it was a wonderful experience to both engineer and construct an experiment we designed. We hope this research may inspire further investment into this issue, and encourage more ARCE students to take advantage of the research facility at Calpoly San Luis Obispo. Most importantly, we hope this research may set precedent to validate the challenge on the “No Bond, No Go” statement.

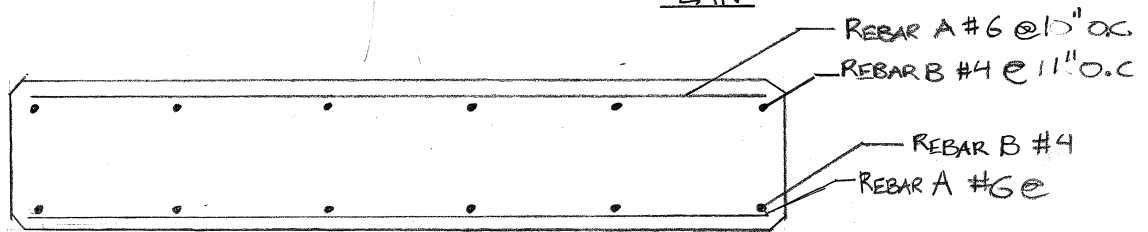
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TESTING SLUG DESIGN



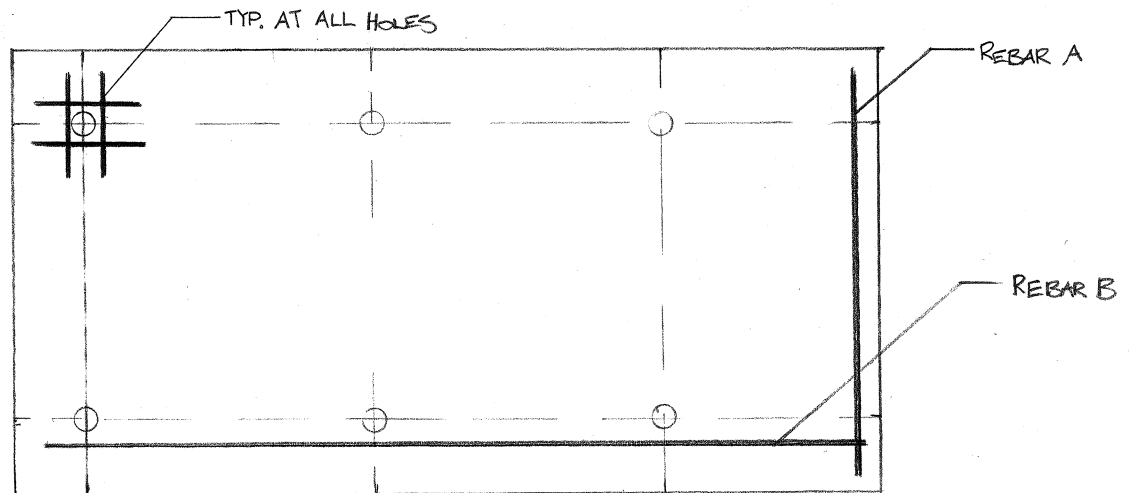
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PLAN

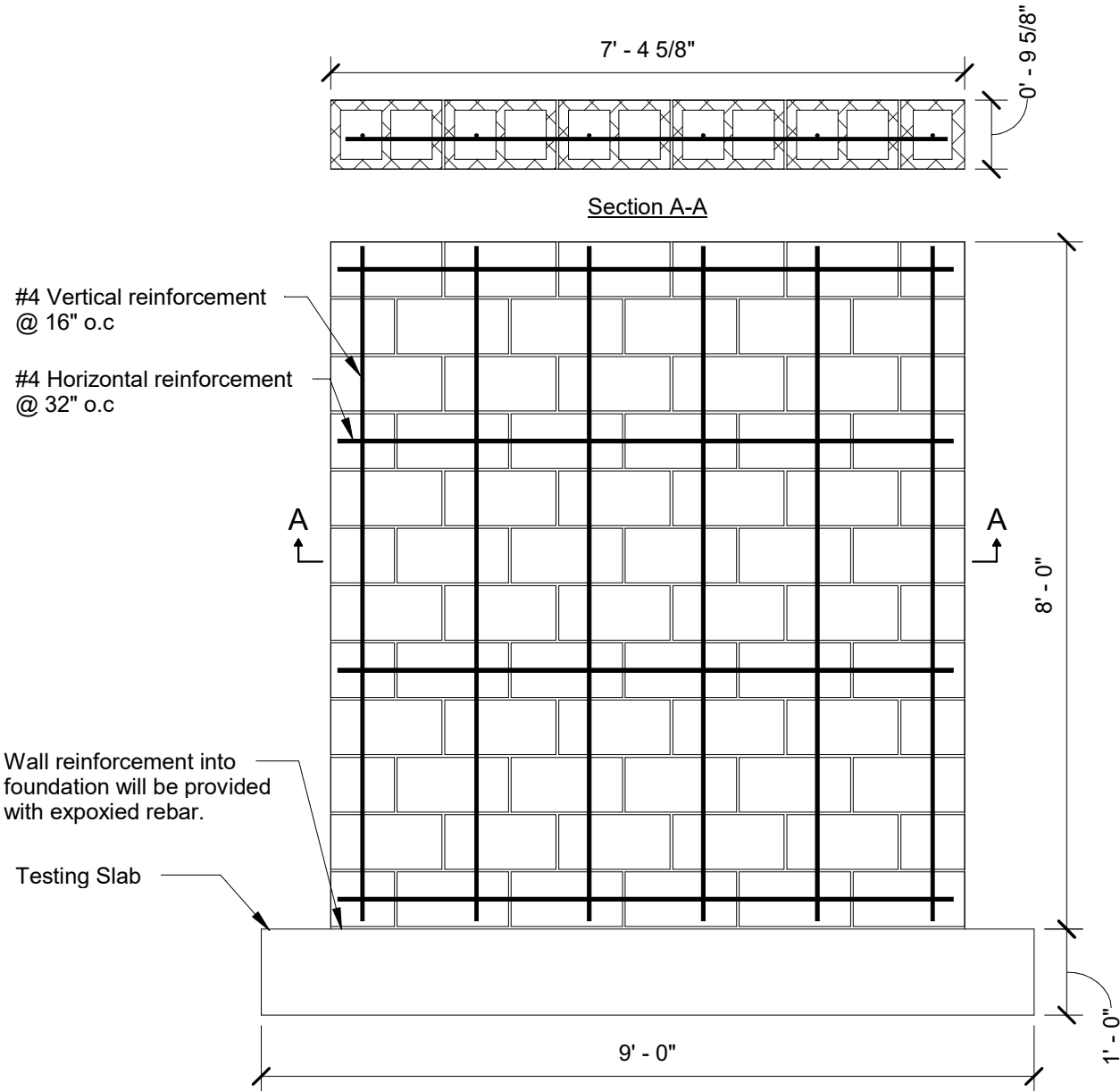


- REBAR A/B TYP. TOP AND BOTTOM

SECTION A-A



REBAR PLAN



- Note:
- 1. Lay masonry in running bond
 - 2. Bed and Head joints to be 3/8" thick.
 - 3. Bond beams where horizontal rebar occurs



STRUCTURAL ENGINEERING

Senior Project: CMU
Wall Core Testing

Wall Section and Elevation

Project number	N/A
Date	6/20/2017
Drawn by	OWA / EAA
Checked by	JPM

S.0

Scale 1/2" = 1'-0"