IMPROVING DUCTILITY OF SLENDER REINFORCED CONCRETE SHEAR WALLS WITH FRP SHEETS AND SPLAY ANCHORS

BY

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SENIOR PROJECT REPORT

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Abstract

The Sylmar earthquake of 1971 caused significant damage to slender, non-ductile reinforced concrete (RC) shear wall buildings in California. A later survey by the Concrete Coalition in 2011, under the guidance of members of the Earthquake Engineering Research Institute (EERI), indicated that there are over 3000 vulnerable concrete buildings in California [8]. This led to City of Los Angeles (LA) Ordinance 193893 enacted in 2015, which requires mandatory upgrades to these concrete buildings by 2035. Current practice to meet the requirements of this ordinance, with respect to RC wall buildings, involves adding new shear walls to the building plan or increasing the cross-sectional area of existing walls using shotcrete. Both options are invasive, costly, and time consuming as they increase the strength of the walls, requiring additional upgrade of the slabs and foundation.

The experimental test program described in this report, being conducted at the California Polytechnic State University (Cal Poly) College of Architecture and Environmental Design (CAED) High Bay Laboratory, will consist of a non-ductile reinforced concrete (RC) wall modelled after pre-1980's walls. The shear wall will be retrofitted with fiber reinforced polymer (FRP) sheets wrapped around the wall boundary elements over the height of the plastic hinge region. FRP splay anchors will also be used to prevent delamination of the FRP sheets bonded to the concrete. The goal of this retrofit application is to provide improved confinement of the concrete to increase the ductility of the wall, with minimal increase in strength. The collaborative team of industry members, faculty advisors, and student researchers hopes to see improvements in the compressive strain capacity in the boundary element concrete and increase the global displacement capacity of the wall. This report provides a literature review of past FRP use on RC shear walls as well as specimen design, experimental test setup, and the construction approach for the Cal Poly wall test program. If effective, the proposed FRP retrofit strategy will provide a cost and time efficient means of improving the seismic performance of slender, non-ductile concrete walls.

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1.0 Introduction

1.1 Background

The Sylmar Earthquake of 1971 caused significant damage and loss of life, which led to the California Mandatory Seismic Retrofit Senate Bill 1953 and the City of LA Ordinance 183893 [7]. A 2017 Occupational of Statewide Health and Planning Department (OSHPD) report indicated that there are 80 hospitals statewide with 197 non-compliant RC buildings [20]. The LA Ordinance has required mandatory retrofits of non-ductile RC buildings by 2035[7]. The concerns involved with these vintage buildings include: (i) recent increase of LA design ground motion value, (ii) little design emphasis placed on inelastic wall response, (iii) less stringent boundary element detailing [7]. Of these concerns, items (ii) and (iii) are of importance to the California Polytechnic State University (Cal Poly) wall test program. West Coast structural engineering firms have seen increased demand for a retrofit strategy addressing the concerns of the LA Ordinance, which the Cal Poly test program seeks to fill [12].

Current practice to improve the response of these walls is to increase cross sectional area by epoxying rebar into existing walls and spraying a layer of shotcrete, or adding new concrete shear walls to the building plan. As both of these approaches improve the strength of the lateral system, they also require upgrade of the slabs and foundation [12]. This process requires complete removal of mechanical, electrical, plumbing, finish, and other interior systems to access the structural elements, making it highly invasive, costly, and time consuming. A few structural engineering firms have started to design fiber reinforced polymer (FRP) retrofit strategies based on FRP retrofitted columns. Some of these strategies are explored in Chapter 2 of this report. Existing experimental tests indicate that column and wall response of FRP retrofits are distinct and that there is a need for FRP retrofitted shear wall testing. Other tests have been performed using FRP to improve strength of concrete shear walls, but little emphasis has been placed on improving ductility through confinement of concrete in the wall boundary elements.

1.2 Project Purpose

The purpose of the research described in this report is to investigate the effectiveness of RC shear walls retrofitted with FRP sheets and through-wall splay anchors and increasing the displacement ductility of the walls. This method is expected to be relatively rapid, simple, and cost effective to apply as it minimally alters existing walls and does not generate significant additional forces that would require upgrade of the overall structural system. The project includes design, construction, and testing of two identical slender non-ductile RC shear walls. The three experimental tests will be performed in the Cal Poly College of Architecture and Environmental Design (CAED) High Bay Laboratory. Specifically, the effectiveness of the retrofit will be assessed via:

Test 1: Virgin non-ductile RC wall
Test 2: Repair wall from Test 1 with FRP Approach
Test 3: Non-ductile RC wall retrofitted with FRP

1.3 Project Team

The Cal Poly wall test program aims to meet a demand for a constructible retrofit strategy for slender non-ductile RC shear walls. The uniqueness of this test program requires engineering and construction support from industry advisors and material suppliers.

The following project team members have provided continual commitment to reach the goals of the Cal Poly wall test program:

- **Industry Advisor:** Garrett Hagen, PE, SE (Degenkolb Engineers) – Proposed the project topic based on an increase of clients with non-ductile RC wall retrofit needs. He is providing his specialized structural engineering experience to ensure the success of the Cal Poly wall test program.

- **FRP Consultant:** Scott Arnold, PE; Reymundo Ortiz; Victor Reyes, PE; Christian Molina (Fyfe) – Engineering/R&D team at Fyfe, a subcompany of Aegion, is completing the retrofit design to meet specified design objectives. Fyfe will also be donating the FRP material for the project.

- **Faculty Advisors:** Anahid Behrouzi, PhD; Peter Laursen, PhD, PE; Allan Hauck, PhD – Faculty from the Cal Poly Architectural Engineering and Construction Management departments provide direction for the project based on prior industry and large-scale experimental testing experience.

- **Graduate Student Peers:** Jerry Luong and Rory de Sevilla, Graduate Students – Worked on all aspects of the project, including: a parametric study to finalize the specimen design, producing specimen drawings, and developing the experimental test setup.

The following suppliers will provide material and design donations to construct the specimen:

- **Concrete Supplier:** Joe Will, Bruce Mercier (Cal Portland) – Produced a concrete mix design that achieves the pre-1980's concrete specifications and will donate concrete to the project.

- **Formwork Design:** Terry Roy; Quincy Dahm (McClone Construction) – Terry is a Cal Poly instructor who began the discussion with the project team to develop a formwork design. The task was transferred to Quincy, who is developing formwork design details for the project. McClone Construction will be providing hardware for the formwork as well.

- **Rebar Supplier:** Kenny Gregoire (LMS Reinforcing) – Donating rebar to the project. This includes a fabricated foundation cage, and loose steel for the wall specimens.

- **Strong Frame Supplier:** Emery Montague, SE (Simpson Strong Tie) – Designed and fabricated a Simpson Strong Frame for this project and use in subsequent large-scale tests in the CAED High Bay Laboratory. This frame has significant cost and will be used to prevent out-of-plane movement of large-scale specimens when tested under large lateral loads.

- **Equipment Supplier:** Kurt Stauss (Zircon) – Equipment donated will be used to obtain accurate location of reinforcement within the concrete wall during the retrofit process, particularly to avoid conflicts with reinforcement during drilling for splay anchors.

- **Concrete Pump Supplier:** (Ryan Stolz Concrete Pumping) – Providing a concrete pump to facilitate pouring of the wall foundation and specimens.

2.0 Literature Review

The use of FRP to strengthen concrete has been seen in beams, columns, bridges, stout shear walls, and many other applications. The following literature review summarizes existing retrofit strategies using FRP on RC shear walls and columns related to the Cal Poly wall test program. No industry application of FRP to confine boundary elements of RC shear walls was found in existing literature.

2.1 FRP Confinement of RC Columns – Experimental Study

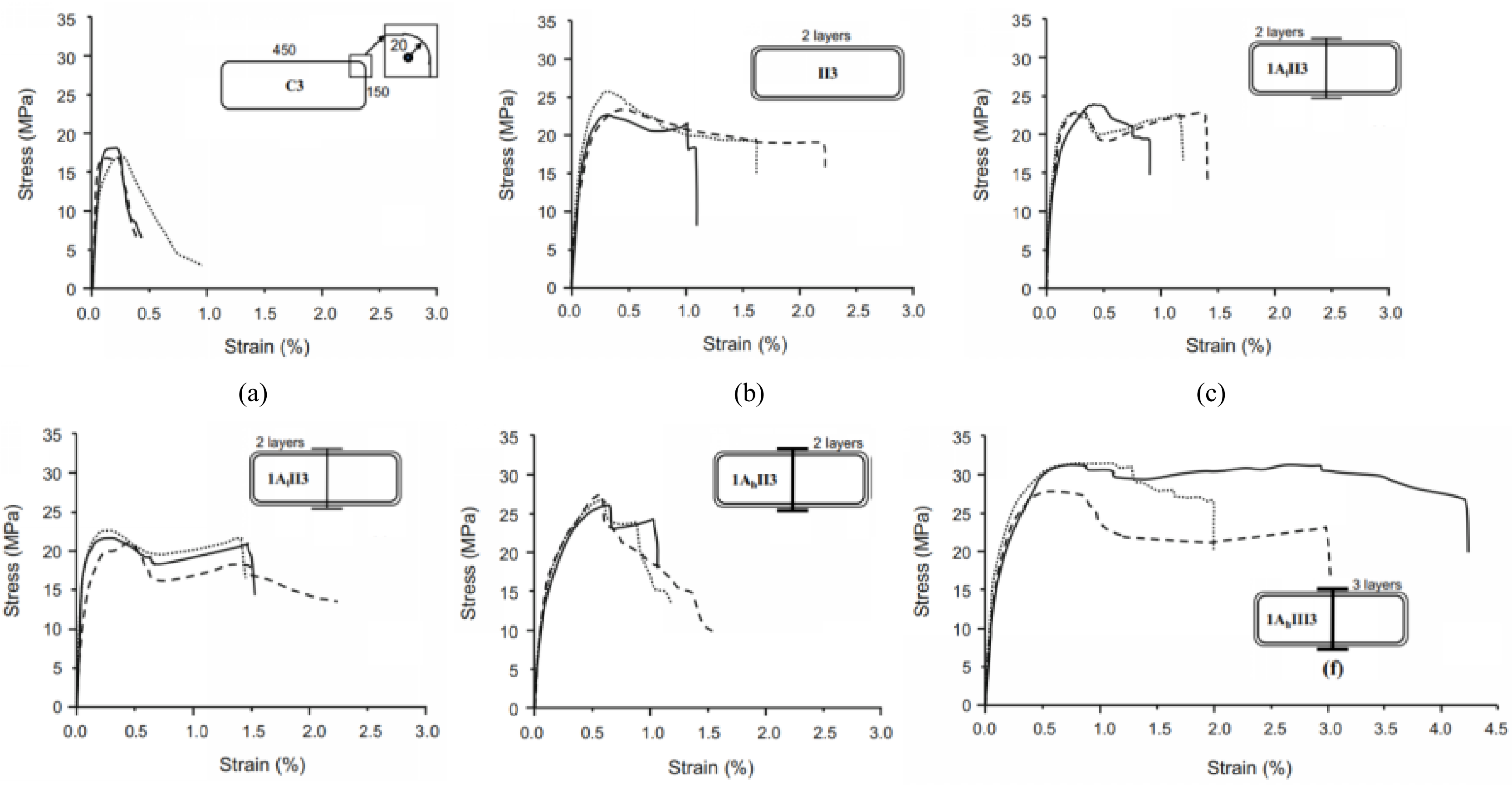
The Triantafillou et al. [25] experimental test program evaluates the improvement in strength and ductility of RC columns retrofitted with FRP. Although RC columns and shear walls are distinct, the test results indicate that FRP can effectively confine concrete with the addition of splay anchors.

A total of 15 column designs were tested with 3 identical columns per design. The 45 specimens differed in cross-sectional aspect ratio (CSAR), use of FRP "spike anchors", capacity of anchors, number of anchors, number of FRP sheet layers, cross-sectional modification, and local strengthening of column corners. Of interest to the Cal Poly wall test program were the effects of confining concrete in columns by varying the number of sheet layers, as well as the number and capacity of anchors. The FRP "spike anchors" are a similar product to the FRP splay anchors that will be utilized in the Cal Poly retrofit. Figure 1(a) shows the stress strain response of the virgin RC column specimen with a CSAR of 3 with no FRP applied. Figures 1(b-f) show results from identical RC columns retrofitted with 2-3 layers of FRP and 0-3 light or heavy anchors. Ductility can be determined by dividing ultimate strain by yield strain.

Triantafillou et al. [25] draws the following conclusions from the stress vs. strain curves presented in Figure 1. Note each comparison is to the virgin column (Specimen C3).

- FRP jackets significantly increase strength (+30-40%) and strain capacity (x2) of RC columns.
- Light anchors with FRP jackets provide no benefit as they fail before providing significant concrete confinement.
- The use of heavy anchors with two layers of FRP sheets improved column confinement, which increased strength by 57%. The strain capacity of these specimens did not improve.
- The use of heavy anchors with three layers of FRP sheets improved column strength by nearly 70% and greatly improved the strain capacity. This indicates that the heavy anchors provide effective confinement and the additional layers of FRP sheets improve strength and ductility.

These findings indicate that FRP sheets are significant in improving concrete confinement in RC columns. Triantafillou et al. [25] points to the importance of using FRP sheets and splay anchors, in combination, to improve confinement and prevent delamination along straight sections of the column. These column tests suggest that a similar application of FRP sheets and splay anchors applied to the boundary elements of shear walls could also lead to significant improvements in ductility.



(a) (b) (c)

(d) (e) (f)

Figure 2.1 - Stress vs. Strain Curves of Triantafillou et al. Test [25]

2.2 Strength of Repaired RC Walls Strengthened with FRP – Experimental Study

The Antoniades et al. [3] test program evaluates the performance of RC shear walls retrofitted with FRP; specifically used to anchor the base and wrap the entire length of the walls. The test program demonstrates how wrapping the length of a repaired RC shear wall changes strength and ductility.

This experimental test program consists of eleven wall tests subjected to cyclic loading. The specimens were tested to failure, retrofitted with FRP sheets, and retested. Displacement ductility, contribution of deformation modes to total displacement, energy dissipation, and stiffness degradation were among the factors evaluated in the study. The results from these tests that inform the Cal Poly wall test program are related to changes in wall strength and ductility performance due to FRP wrapping.

Each wall was tested first with no retrofit strategy to provide a base-line performance. All walls were then repaired by removing cracked concrete, lap-splicing fractured steel bars, adding new confinement hoops and web reinforcement, and casting non-shrink, high strength mortar to replace the portions of lost concrete cross-section. All walls, except for Specimen LSW3, were repaired with FRP techniques shown in Figure 2.2. These repairs include carbon and glass FRP to anchor the wall to the foundation, and glass FRP used to wrap the entire wall. The repair objective was to increase flexural strength, shear strength, and ductility. Note the LS and MS wall series have a shear span ratio of 1.0 and 1.5, respectively.

Compared with LSW3, all FRP wrapped walls increased in strength (+ 2 - 48%) shown in Table 2.1 as did the displacement ductility factors shown in Table 2.2. Based on hysteretic response, the FRP wrapped walls also generally had improved energy dissipation and more gradual stiffness degradation when compared with the LSW3 wall, though not when compared with the base-line specimens. This trend of seismic performance is shown for wall LSW5 in Figures 2.3.

Antoniades et al.[3] attributes the inferior ductility of the FRP strengthened walls to: (i) fracture of rebar that occurs due to the FRP concentrating inelastic deformation at a single flexural crack, (ii) inelastic behavior of the wall occurs after failure of the FRP sheets and (iii) very low efficiency of FRP jackets with regard to providing confinement in long straight sections of the wall. Although the FRP strengthening improved both flexural and shear strength, the hysteretic response indicates no improvement in seismic performance of FRP repaired walls beyond the virgin wall tests.

2.2.1 Comparison to Cal Poly Wall Test Program

The Antoniades et al. [3] test differs from the Cal Poly wall test program in the following ways:

- No FRP splay anchors were used to maintain the bond between FRP sheets and concrete.
- Little emphasis was placed on FRP used to confine concrete, specifically in the boundary elements.
- The FRP was wrapped continuously around the entire wall length.
- FRP was used for repaired on previously damaged walls rather than retrofitting undamaged walls.
- Analysis was conducted on walls with relatively short shear span ratios that experienced both shear and flexure dominated failure.

Antoniades et al. [3] indicates that seismic response of RC shear walls repaired with FRP does not improve over virgin walls, particularly with respect to ductility. The Cal Poly wall test program seeks to employ a displacement demand improvement instead of a strength increase improvement seen these previous wall tests. The conclusion from the report regarding the low efficiency of FRP jackets for wall confinement, indicates that splay anchors may be a successful solution.

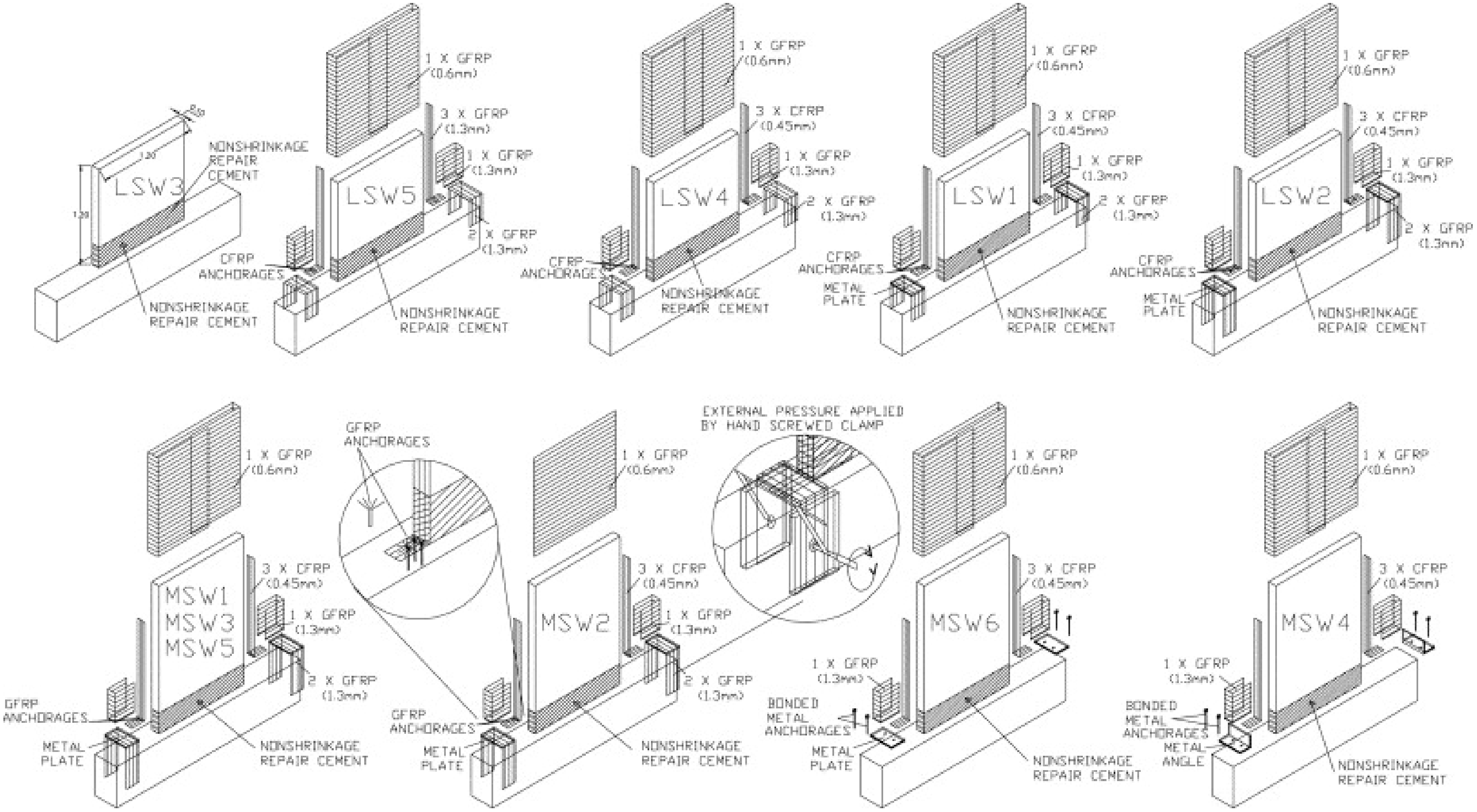
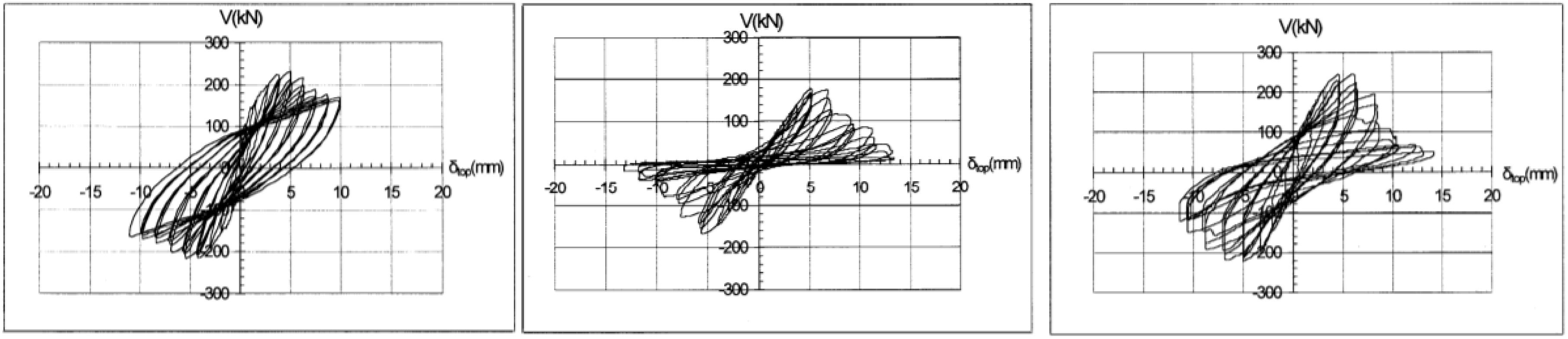


Figure 2.2 – Repair and Strengthening Techniques of Antoniades et al Test [3]



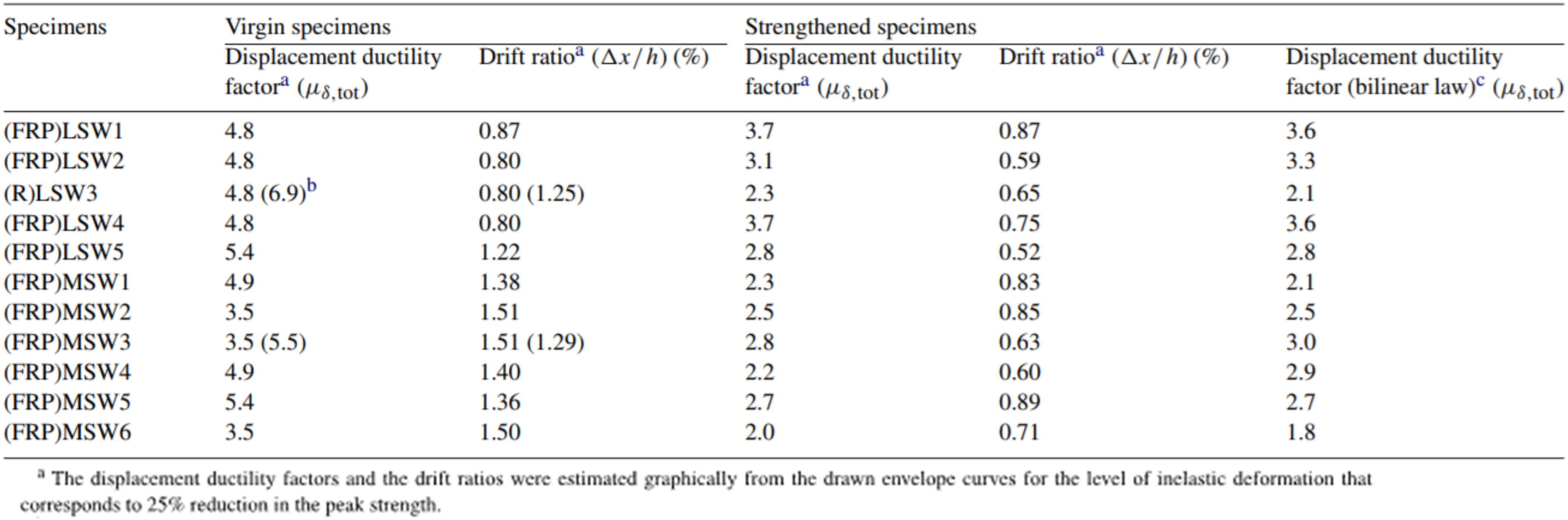
(a) Virgin Wall (b) Repaired Wall without FRP (c) Repaired with FRP

Figure 2.3 – Hysteresis Curves of Antoniades et al. Test [3]

Table 2.1 – Test Results of Strength of Antoniades et al Walls [3]

Specimen	Virgin V_{R0} (kN)	Strengthened V_{meas} (kN)	Strength increase (%) $(V_{\text{meas}} - 0.94V_{R0})/(0.94V_{R0})$
FRPLSW1	262.0	325.4	32
FRPLSW2	191.0	200.8	12
RLSW3	191.0 (250.0 when $N = 165$ kN)	178.9 ($N = 0$ kN)	0
FRPLSW4	232.0	244.9	12
FRPLSW5	247.0	236.9	2
FRPMSW1	197.0	243.9	32
FRPMSW2	124.0	172.4	48
FRPMSW3	124.0 (176.0 when $N = 165$ kN)	164.3 ($N = 0$ kN)	41
FRPMSW4	158.0	180.8	22
FRPMSW5	187.0	210.8	20
FRPMSW6	202.0	200.2	5

Table 2.2 – Test Results of Ductility of Walls [3]



Specimens	Virgin specimens		Strengthened specimens		
	Displacement ductility factor[a] ($\mu_{\delta,\mathrm{tot}}$)	Drift ratio[a] ($\Delta x/h$) (%)	Displacement ductility factor[a] ($\mu_{\delta,\mathrm{tot}}$)	Drift ratio[a] ($\Delta x/h$) (%)	Displacement ductility factor (bilinear law)[c] ($\mu_{\delta,\mathrm{tot}}$)
(FRP)LSW1	4.8	0.87	3.7	0.87	3.6
(FRP)LSW2	4.8	0.80	3.1	0.59	3.3
(R)LSW3	4.8 (6.9)[b]	0.80 (1.25)	2.3	0.65	2.1
(FRP)LSW4	4.8	0.80	3.7	0.75	3.6
(FRP)LSW5	5.4	1.22	2.8	0.52	2.8
(FRP)MSW1	4.9	1.38	2.3	0.83	2.1
(FRP)MSW2	3.5	1.51	2.5	0.85	2.5
(FRP)MSW3	3.5 (5.5)	1.51 (1.29)	2.8	0.63	3.0
(FRP)MSW4	4.9	1.40	2.2	0.60	2.9
(FRP)MSW5	5.4	1.36	2.7	0.89	2.7
(FRP)MSW6	3.5	1.50	2.0	0.71	1.8

[a] The displacement ductility factors and the drift ratios were estimated graphically from the drawn envelope curves for the level of inelastic deformation that corresponds to 25% reduction in the peak strength.

2.3 Effect of Confining of Shear Wall Boundary Elements with FRP – Analytical Study

The Mostofinejad et al. [19] analytical study analyzes the ductility and strength of RC shear walls confined with FRP using the ABAQUS 6.7 modelling software [1]. The test applies similar retrofit strategies as the Cal Poly wall test program, but examines its effectiveness using analytical modelling rather than experimental testing.

2.3.1 Model Calibration

To validate the accuracy of the model, two walls without FRP and one column with and without FRP were simulated in ABAQUS 6.7 [1] and compared to experimental results. Figure 2.4 shows a wall designed and tested experimentally by Perry et al. [21] with a strength approach. Figure 2.5 shows a wall designed by Thomsen and Wallace [24] with a displacement demand approach. The comparison of experimental and analytical models showed that the computer model was able to simulate the cracking pattern, and load displacement curves of the reinforced concrete with good accuracy.

As there is little data available on the effect of slender concrete shear walls strengthened with FRP, the computer model was compared with a column designed by Hosseini et al. [17] shown in Figure 2.6. Two identical columns were tested with and without FRP wrapping to capture the change in column response. Analytical results of the column without FRP was comparable to the experiment, including concrete crushing in the plastic hinge zone and good agreement between load-displacement curves. The analytical model for column with FRP had similar stresses in the FRP sheets as the experiment as well as good accuracy with respect to the load-displacement response. As a note, the computer software used in the Mostofinejad et al. [19] study is a general finite element modelling software used to analyze structures built from a wide range of materials subject to varying types of loading. This required that significant parameter adjustments had to be made to calibrate the model to accurately capture the experimental response of the FRP wrapped concrete column, and therefore the subsequent concrete shear walls.

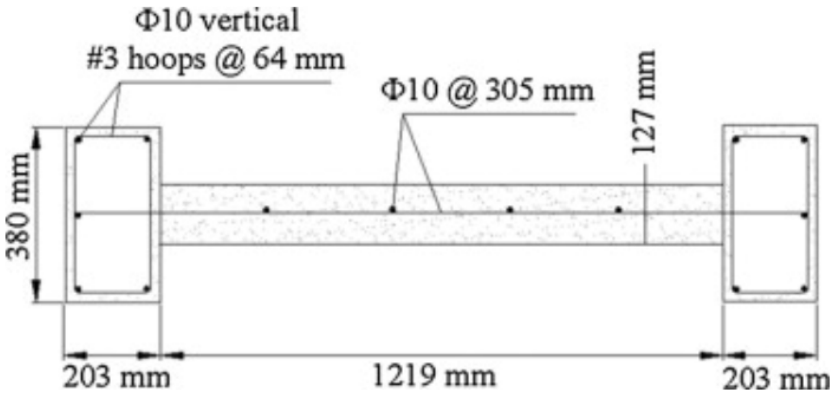


Figure 2.4 – Perry et al. Wall Designed with Strength Approach [21]

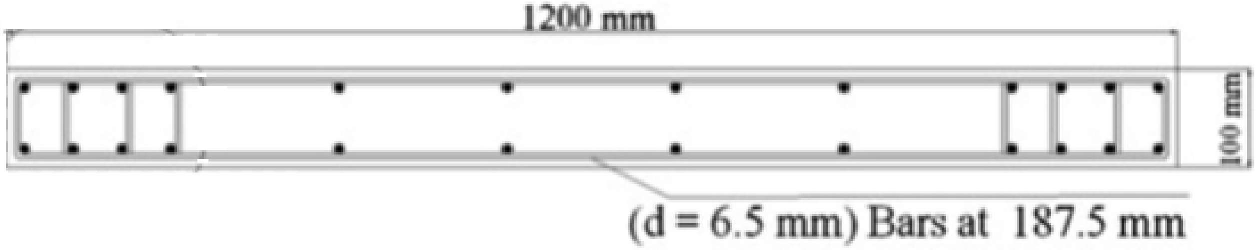


Figure 2.5 – Thomsen and Wallace Wall Designed with Displacement Demand Approach [24]

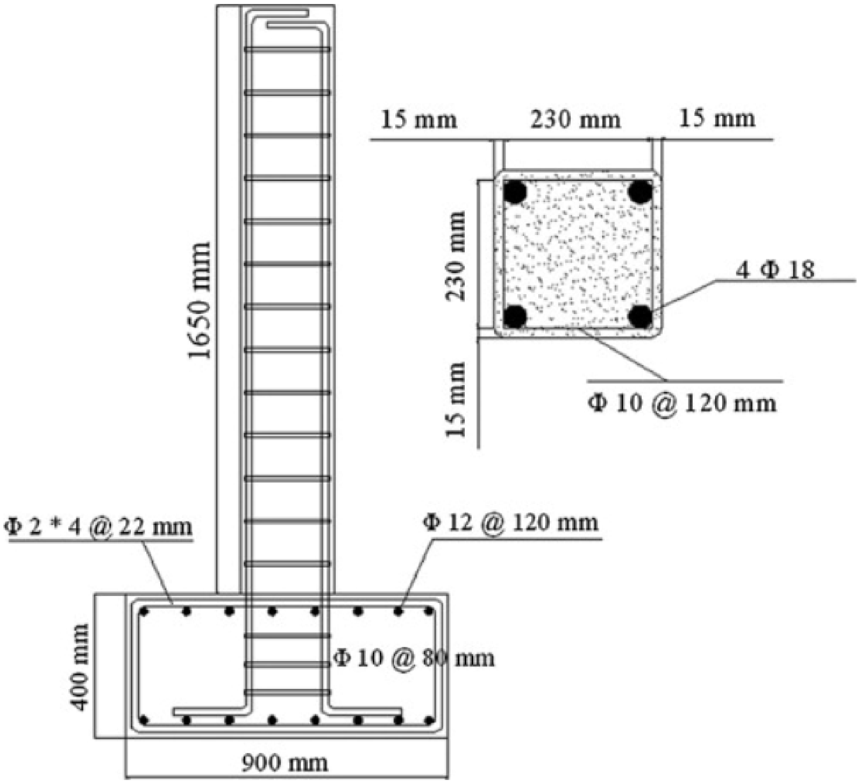


Figure 2.6 – Hosseini et al. Column [17]

2.3.3 Test Results

The Mostofinejad et al. [19] analytical study was conducted for two slender RC shear wall designs. The first wall SH3 was designed on a stress-based approach shown in Figure 2.7, while the second wall RW1 was the Thomsen and Wallace [24] wall in Figure 2.5 designed with a displacement approach. The analytical study involved varying the number of layers of FRP, and the height of the FRP. Although the effect of changing stirrups was also considered in this study, it is the FRP metrics that relate closely to the Cal Poly wall test program.

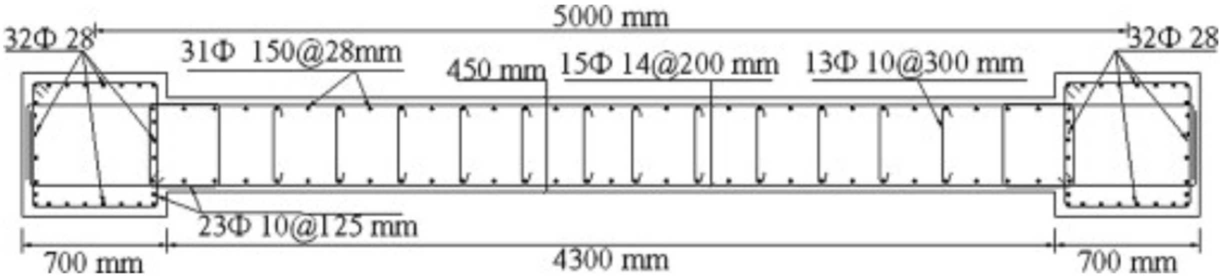


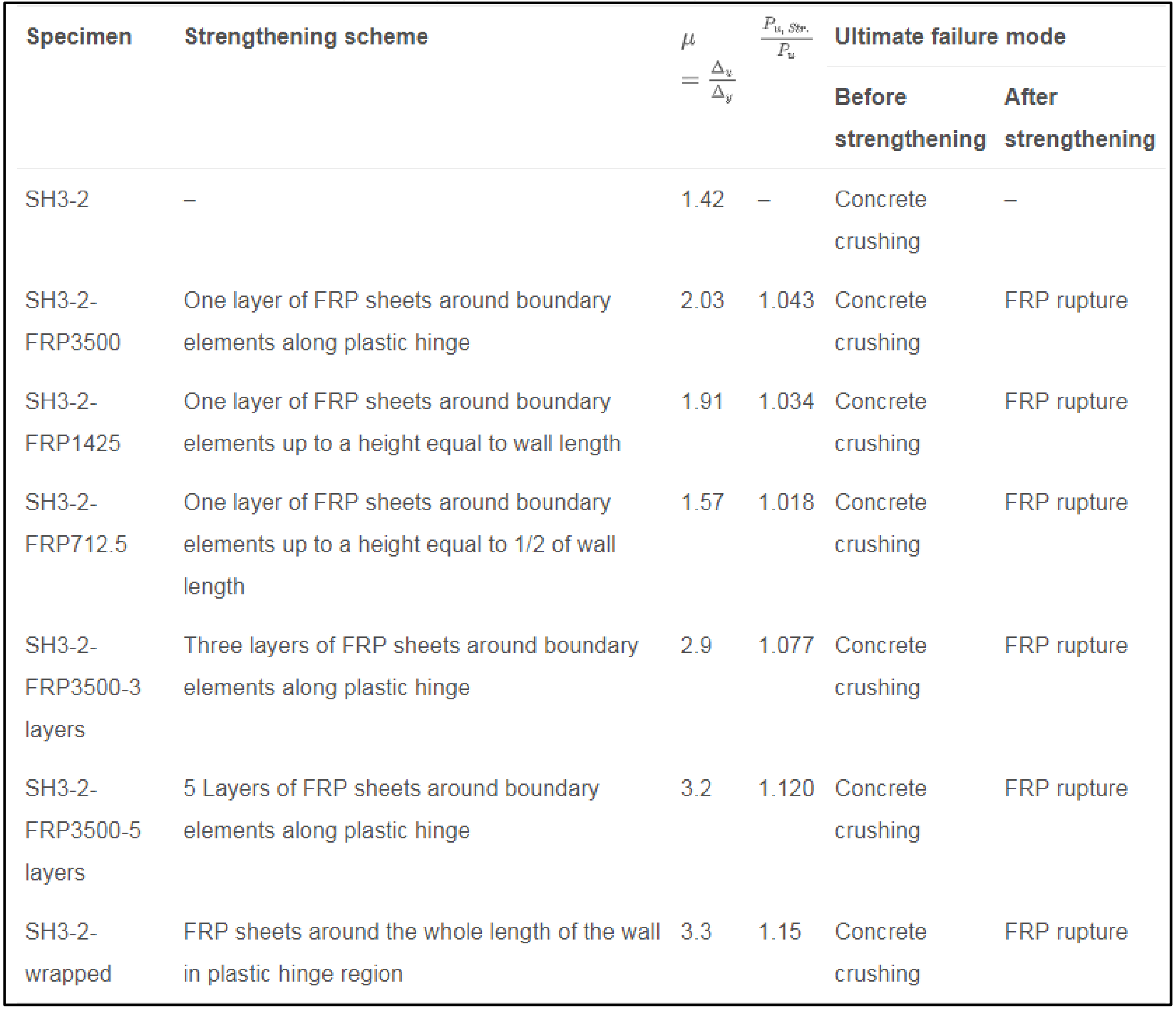
Figure 2.7 – Mostofinejad et al. Wall SH3

The results of the analytical study for the two walls are shown in Tables 2.3 and 2.4 below. The following conclusions can be made from the test:

- Applying one layer of FRP around the boundary elements in the plastic hinge region of poorly detailed concrete shear walls has significant effects on displacement, but minimal effects for well detailed walls.
- Additional layers of FRP result in increased displacement capacity.
- Wrapping FRP around the entire length of the wall yields little improvement in displacement capacity, when compared with FRP wrapped only around the boundary elements. Wrapping the entire specimen does show improvement in the strength capacity of the walls.

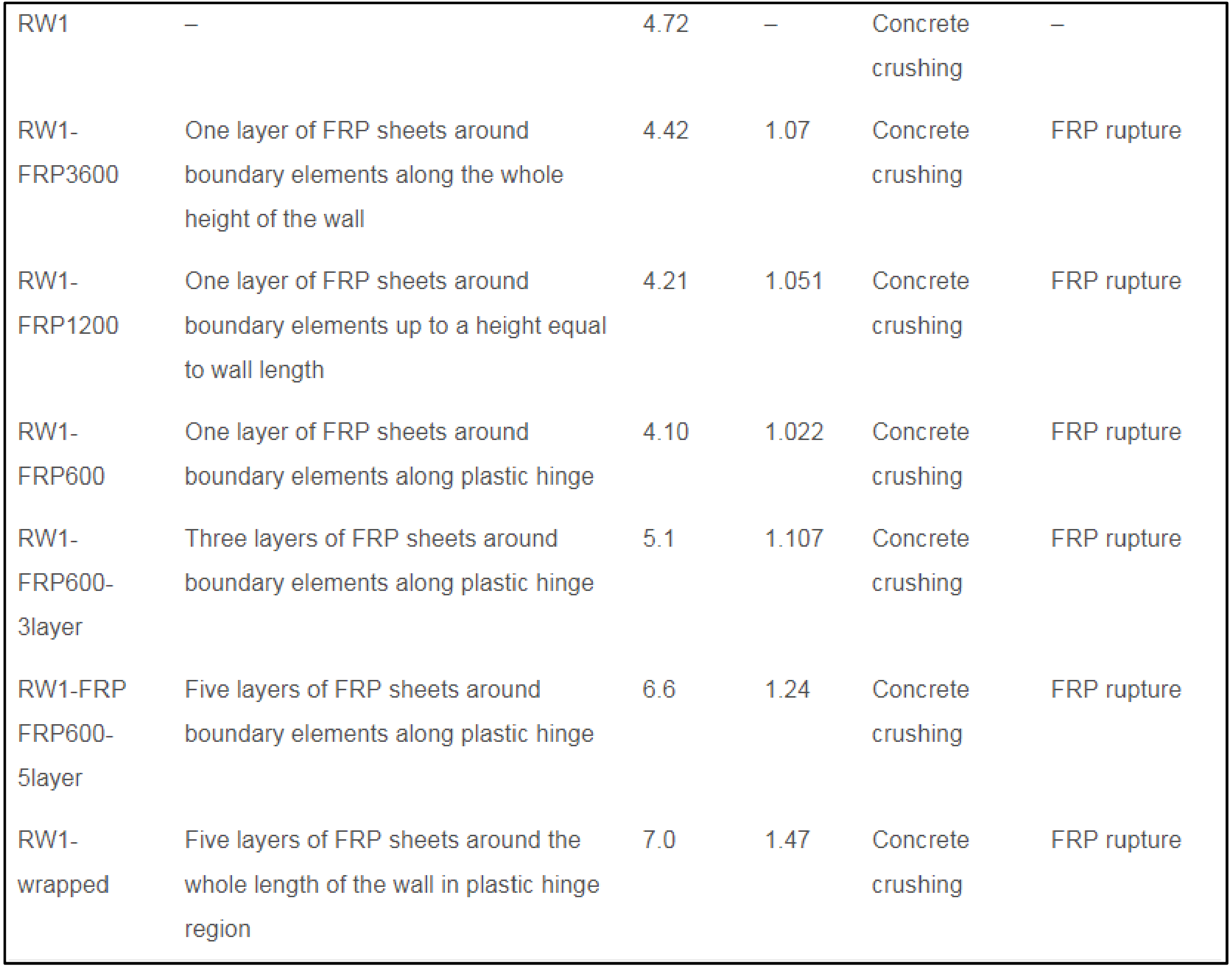
In summary, it is more economical to wrap only the boundary elements along the plastic hinge regions of concrete shear walls to improve seismic performance.

Table 2.3 – Summary of Strength Designed Wall in Mostofinejad Study [19]



Specimen	**Strengthening scheme**	$\mu = \frac{\Delta_u}{\Delta_y}$	$\frac{P_{u,\ Str.}}{P_u}$	**Ultimate failure mode**	
				Before strengthening	**After strengthening**
SH3-2	–	1.42	–	Concrete crushing	–
SH3-2-FRP3500	One layer of FRP sheets around boundary elements along plastic hinge	2.03	1.043	Concrete crushing	FRP rupture
SH3-2-FRP1425	One layer of FRP sheets around boundary elements up to a height equal to wall length	1.91	1.034	Concrete crushing	FRP rupture
SH3-2-FRP712.5	One layer of FRP sheets around boundary elements up to a height equal to 1/2 of wall length	1.57	1.018	Concrete crushing	FRP rupture
SH3-2-FRP3500-3 layers	Three layers of FRP sheets around boundary elements along plastic hinge	2.9	1.077	Concrete crushing	FRP rupture
SH3-2-FRP3500-5 layers	5 Layers of FRP sheets around boundary elements along plastic hinge	3.2	1.120	Concrete crushing	FRP rupture
SH3-2-wrapped	FRP sheets around the whole length of the wall in plastic hinge region	3.3	1.15	Concrete crushing	FRP rupture

Table 2.4 – Summary of Displacement Designed Wall in Mostofinejad Study [19]



RW1	–	4.72	–	Concrete crushing	–
RW1-FRP3600	One layer of FRP sheets around boundary elements along the whole height of the wall	4.42	1.07	Concrete crushing	FRP rupture
RW1-FRP1200	One layer of FRP sheets around boundary elements up to a height equal to wall length	4.21	1.051	Concrete crushing	FRP rupture
RW1-FRP600	One layer of FRP sheets around boundary elements along plastic hinge	4.10	1.022	Concrete crushing	FRP rupture
RW1-FRP600-3layer	Three layers of FRP sheets around boundary elements along plastic hinge	5.1	1.107	Concrete crushing	FRP rupture
RW1-FRP FRP600-5layer	Five layers of FRP sheets around boundary elements along plastic hinge	6.6	1.24	Concrete crushing	FRP rupture
RW1-wrapped	Five layers of FRP sheets around the whole length of the wall in plastic hinge region	7.0	1.47	Concrete crushing	FRP rupture

2.3.3 Comparison to Cal Poly Wall Test Program

The Mostofinejad et al. [19] study is highly comparable the Cal Poly wall test program, the major differences being that this analytical study:

- Uses a computer model calibrated using an FRP wrapped column and virgin RC walls, which may not fully capture the real behavior of FRP wrapped walls that would be evident in experimental testing.
- Does not consider the effects of FRP delamination nor FRP splay anchors.

The Mostofinejad et al. [19] study indicates that the ductility of poorly detailed, slender RC shear walls can be greatly improved when wrapped with FRP sheets. To prevent increases in wall strength capacity, the use of FRP sheets should be limited to only within the plastic hinge region of boundary elements. This evidence informs the Cal Poly wall test program.

3.0 Specimen Design

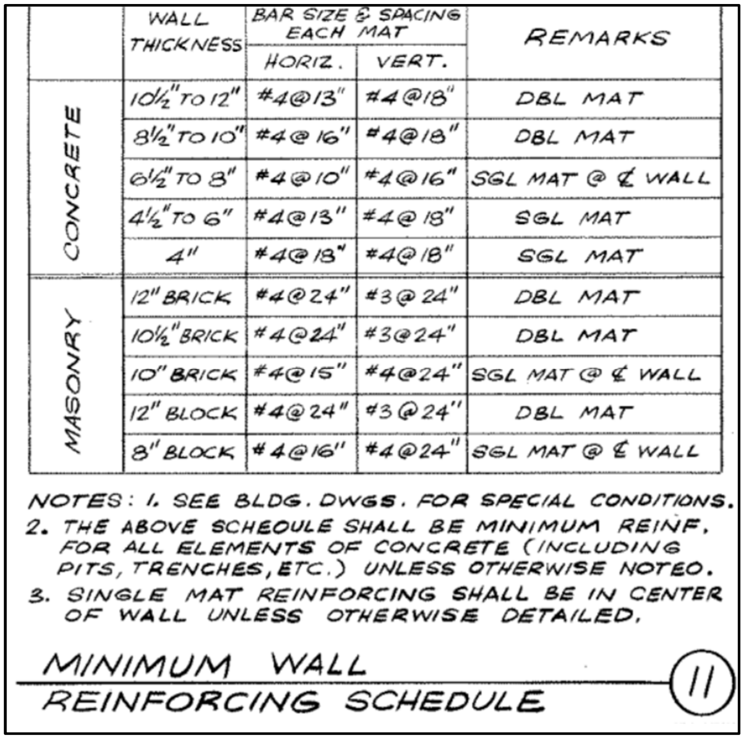
This section summarizes the specimen design for the Cal Poly wall test program. In addition to outcomes of a parametric study conducted that define the wall design parameters, there is also a discussion of material specifications for concrete, steel reinforcement, and FRP to be used in the wall specimens.

3.1 Design Intent

The design of the Cal Poly specimens are based upon pre-1980's non-ductile RC walls. Structural designers of this time period focused on elastic wall response, neglecting displacement demand and necessary boundary element detailing. The design goal for the wall test specimen is to achieve a flexure-controlled failure and that the FRP confine the boundary elements and increase displacement capacity.

3.2 Historical Basis for Wall Specimen Design

The final half-scale wall specimen design was modeled after a 1958 building, which is representative of detailing prior to the 1976 Universal Building Code (UBC) [26]. Minimal detailing is provided for boundary elements, indicating that there was no special consideration for these regions before 1976. Rebar layout was determined based on values from Figure 3.1, along with reinforcing ratio and spacing requirements of the time period.



	WALL THICKNESS	BAR SIZE & SPACING EACH MAT		REMARKS
		HORIZ.	VERT.	
CONCRETE	10½" TO 12"	#4@13"	#4@18"	DBL MAT
	8½" TO 10"	#4@16"	#4@18"	DBL MAT
	6½" TO 8"	#4@10"	#4@16"	SGL MAT @ ℄ WALL
	4½" TO 6"	#4@13"	#4@18"	SGL MAT
	4"	#4@18"	#4@18"	SGL MAT
MASONRY	12" BRICK	#4@24"	#3@24"	DBL MAT
	10½" BRICK	#4@24"	#3@24"	DBL MAT
	10" BRICK	#4@15"	#4@24"	SGL MAT @ ℄ WALL
	12" BLOCK	#4@24"	#3@24"	DBL MAT
	8" BLOCK	#4@16"	#4@24"	SGL MAT @ ℄ WALL

NOTES: 1. SEE BLDG. DWGS. FOR SPECIAL CONDITIONS.
2. THE ABOVE SCHEDULE SHALL BE MINIMUM REINF. FOR ALL ELEMENTS OF CONCRETE (INCLUDING PITS, TRENCHES, ETC.) UNLESS OTHERWISE NOTED.
3. SINGLE MAT REINFORCING SHALL BE IN CENTER OF WALL UNLESS OTHERWISE DETAILED.

MINIMUM WALL REINFORCING SCHEDULE

Figure 3.1 – Minimum Wall Reinforcing Schedule [15]

3.3 Parametric Study to Finalize Wall Specimen Design

A parametric study was conducted in SpColumn [23] by adjusting the length, height, width, rebar layout, and concrete strength to determine an ideal wall specimen. The following parameters indicate target ranges based on pre-1980's non-ductile walls and testing constraints at the Cal Poly (CAED) High Bay Laboratory. Table 3.1 gives the values investigated in the parametric study.

- **Shear Span** (h/l_w) – The height of the wall was determined by the height-to-length ratio (or, shear span). A ratio of 3:1 classifies a pure flexure response per ASCE 41 [4]. In the High Bay Laboratory there is a maximum allowable wall specimen height of roughly 12 feet. The length of the wall was determined to be approximately 5 feet to achieve a final shear span ratio of 2.5, which is anticipated to result in flexure dominated response.

- **Cross-Sectional Aspect Ratio** (CSAR, l_w/t) – The cross-sectional aspect ratio was adjusted to meet the CSAR of typical shear walls in pre 1980's design which was 15-20. A CSAR in this range would put the wall width between 2.4 and 3.2 inches. Constructability dictates that the wall was not thinner than 5 inches. The final CSAR was 12.

- **Maximum Rebar Spacing** – The UBC [26], during the representative time period, requires a maximum 18 inch rebar spacing. At full-scale, the Cal Poly wall specimen falls under this requirement.

- **Reinforcing Ratio** (ρ_v)– The UBC [26] designates a minimum reinforcing ratio of 0.25% of the gross wall area. This ratio, the maximum rebar spacing, and the rebar schedule in Figure 3.1 determined the final layout of rebar in the wall specimen which was #3 at 14.3 inches on center.

- **Axial Load** (P) –Although ACI 318 [2] dictates $2.5\%A_g f'_c$ should be used, however with the reduced vertical reinforcement ratio a value of $1\%A_g f'_c$ will be used. A concrete compressive strength of 4.5 ksi is expected for the specified 3 ksi mix.

- **Lateral Load** (V) – The lateral load was determined based on the flexural capacity of the wall determined using the SpColumn [23] software divided by the height of the wall.

- **Neutral Axis** (c) – The neutral axis depth of the wall defines the length of the boundary element, and therefore the area of the FRP wrap. An adequate neutral axis depth for the wall is necessary so the FRP anchors have sufficient spacing edge distances required to confine the boundary elements. The neutral axis depth was determined through analysis in SpColumn [23].

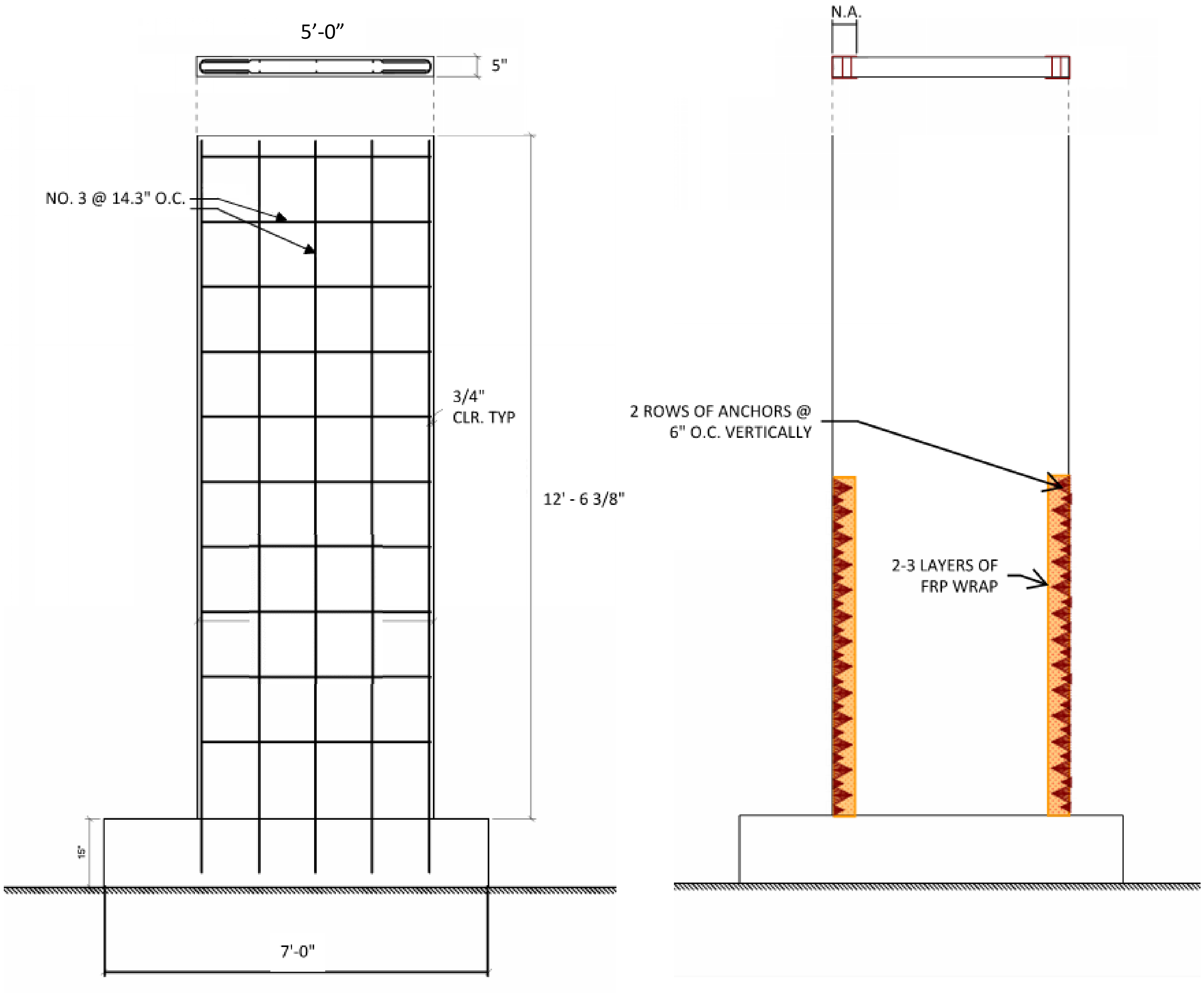
Table 3.1 – Parametric Study Values

	Desired	**Analyzed**	**Selected**
Wall Dimension			
Length (in)	~48	42-62	60
Width (in)	5-6	3-4	5
Height (ft)	12*	11-13	12.5
Rebar Layout			
Vertical Rebar (#3 @ x" O.C.)	16-24	12.4-19.8	14.3
Horizontal Rebar (#3 @ x" O.C.)	10-24	11-14.3	14.3
Vertical Reinf. Ratio, ρ_v (%)	-	0.20-0.47	0.44
Material Strength			
Concrete Comp. Strength, F'_c (ksi)	-	3-4	3
Steel Yield Strength, F_y (ksi)	40	40	40
Design Parameter			
Shear Span (h/l_w)	3	2.13-3.41	2.5
CSAR (l_w/t)	15-20	7.04-20.68	12
Axial Load (1%*f'c*A_g, k)	-	8.37-16.75	13.5
Nuetral Axis	-	2.28-3.99	3.73

*Based on Lab Restrictions

3.4 Final Shear Wall Design

Figure 3.2 shows the final specimen design including dimensions, rebar layout, and assumed FRP layout. Although the FRP design is not finalized, the neutral axis distance defines the length of the wrap and the plastic hinge region defines the height of the wrap. It is expected that there will be two rows of splay anchors which are spaced based on minimum spacing requirements from the Fyfe Engineering and R&D team members that are consulting on the project.



(a) (b)

Figure 3.2 – Final Wall Design [14]

3.5 FRP Design

Current design of concrete shear walls dictates increased vertical and confinement reinforcing in the boundary elements compared to pre-1980's designs. This requirement is to resist high tensile and compressive stresses that will occur in the boundary elements during a seismic event. In the proposed retrofit, the FRP will provide concrete confinement in lieu of hoops, but likely no additional strength to the wall. The improved confinement will increase the displacement capacity and ductility of the wall. See Sections 3.6, 5.1, and Appendix A.1 for details on the FRP material and installation.

3.6 Materials

The concrete used will be a 3000 psi mix provided by Cal Portland. The mix uses a 3/8 inch coarse, angular pea gravel to act as a half-scale ¾ inch aggregate used in normal concrete. See Appendix A.2 for mix specifications. The vertical and horizontal reinforcement, provided by LMS Reinforcing, will be #3 steel bar with a 40 ksi yield strength to be consistent with the strength of pre-1980's reinforcement. A steel mill certification can be found in the Appendix A.3.

The proposed FRP product is the TYFO SCH-41[10] provided by Fyfe, a subcompany of Aegion. This product is a uni-directional carbon fiber sheet material which is coated in a Tyfo S Epoxy[11] as seen in Figure 3.3. In the application for the Cal Poly wall test program, the high strength of the carbon fiber is used to confine the concrete in the boundary elements. A TYFO SCH Composite Anchor [9] is provided through the wall specimen at the end of the boundary element to prevent delamination of the FRP sheets. Figure 3.4 shows an FRP anchor which goes through a wall and joins with the FRP wrap.

Figure 3.3 – Schematic Diagram of FRP Sheet [18]

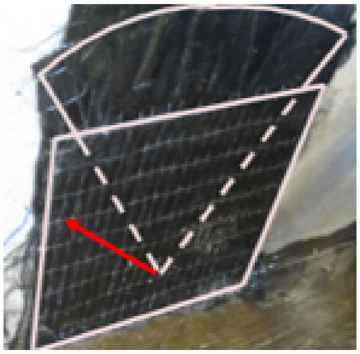


Figure 3.4 – FRP Splay Anchor Under a Wall [18]

4.0 Experimental Test Setup

4.1 Test Setup Overview

Figures 4.1 and 4.2 show an overview of the experimental test setup in the Cal Poly High Bay Laboratory; specific components are discussed in Section 4.2-4.6 of this report. The strong floor within the High Bay Laboratory has 1.5 inch bolt holes at 3 feet on center which will be used to anchor the specimen. Lateral load will be applied to the specimen using a uniaxial actuator fixed to the steel reaction frame. A hydraulic jack, not shown in Figure 4.1 for clarity, will apply axial load vertically to the specimen.

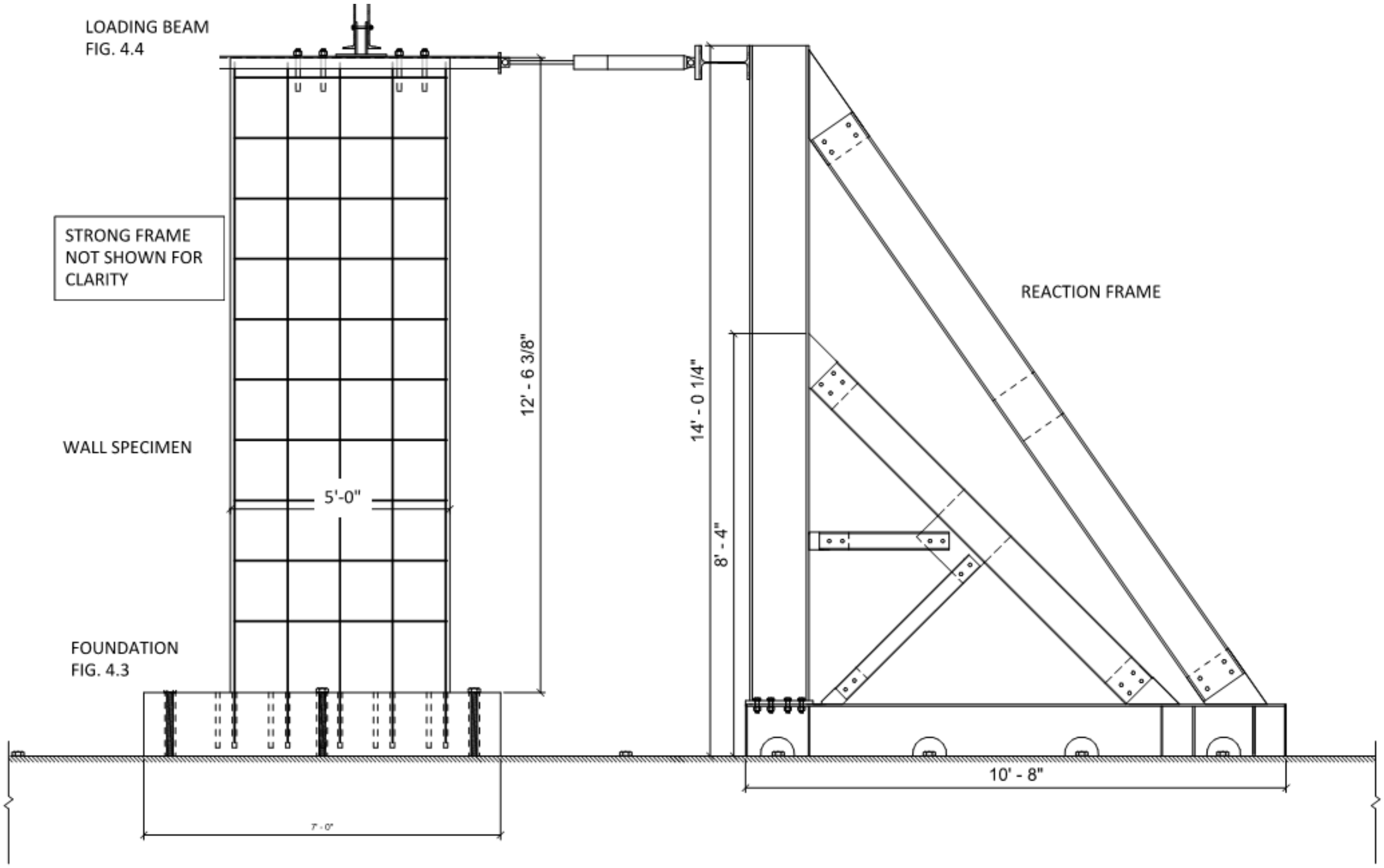


Figure 4.1 – Experimental Test Setup in Cal Poly High Bay Laboratory, Elevation [14]

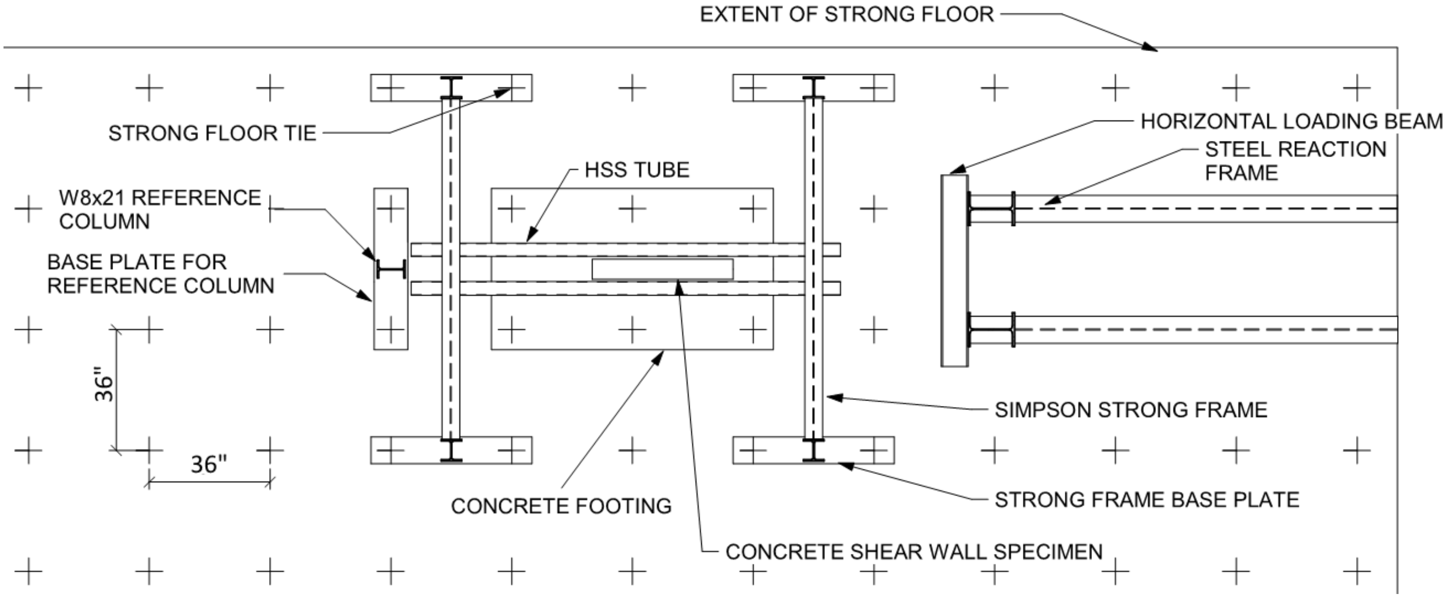
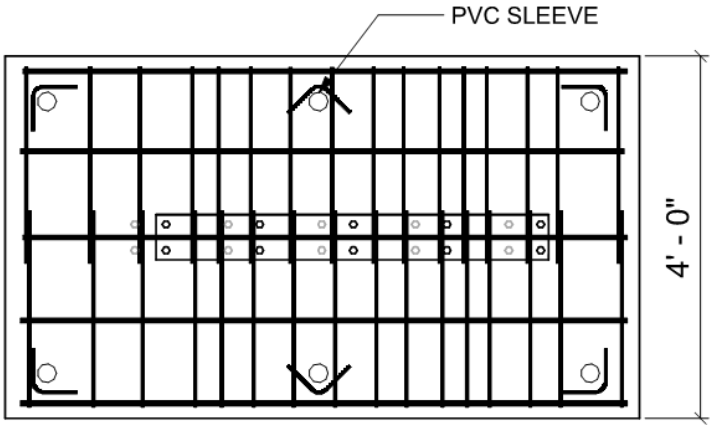


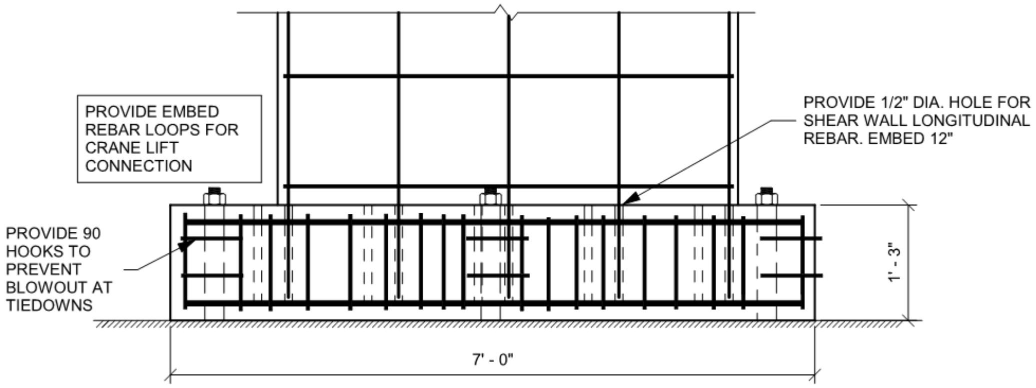
Figure 4.2 – Experimental Test Setup in Cal Poly High Bay Laboratory, Plan [14]

4.2 Foundation

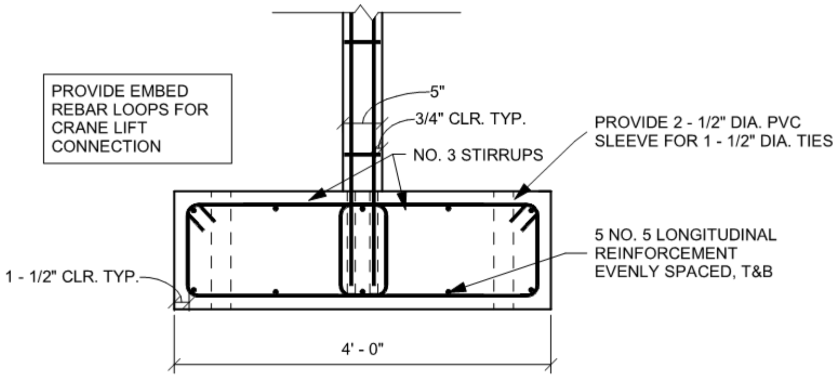
The foundation designed to secure the wall specimen to the strong floor is meant to be used for future projects in the Cal Poly High Bay Lab. Each wall specimen is connected to the foundation using epoxied vertical reinforcement which will create a comparable connection for the first and second wall specimens The epoxied rebar for the second specimen will be shifted over 4 inches from that of the first wall. The foundation has 2.5 inch PVC sleeves through which six 1.5 inch bolts are secured to the strong floor. The foundation can be moved for future tests by connecting a crane attachment into embedded rebar loops. See Figure 4.3 for the foundation layout.



(a) Transverse Section of Foundation



(b) Longitudinal Section of Foundation



(c) Plan of Foundation

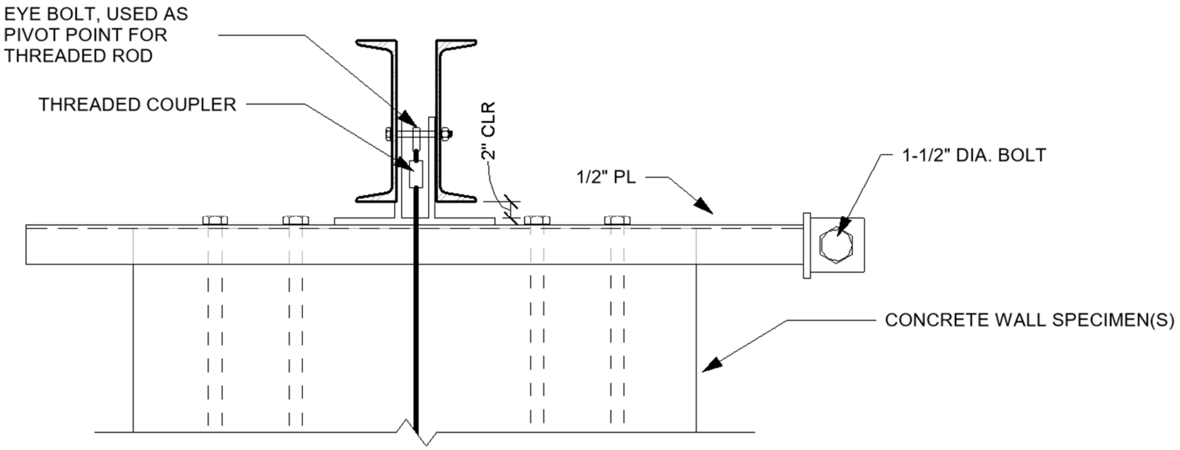
Figure 4.3 – Cal Poly Test Wall Foundation [14]

4.3 Reaction Frame

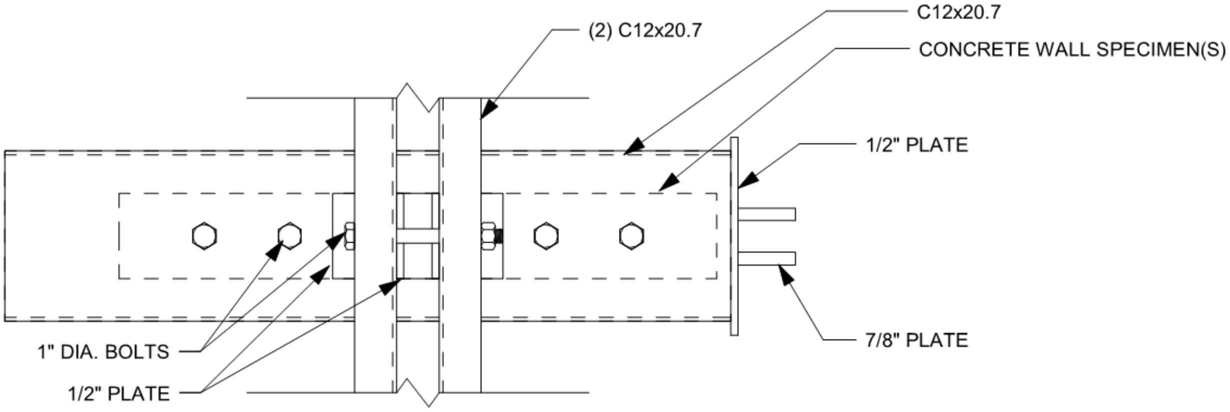
The reaction frame shown on the right hand side of Figure 4.1 is used as a support for a horizontal actuator which provides lateral force to the wall. As shown in Figure 4.2, the lateral load is resisted by two reaction frames connected by a horizontal beam. The existing steel reaction frame in the High Bay lab was analyzed in Luong and Brown [13] and determined that for the anticipated stiffness of the RC wall specimens to be tested, upgrades were necessary. Therefore the reaction frame was redesigned with an additional brace.

4.4 Cyclic Load Application

Lateral load is applied to the top of the test specimens using a Enerpac RR5013 uniaxial actuator with a 110 kip compression capacity and 23.6 kip tension capacity. This actuator is fixed to the reaction frame at 13 feet, 8 inches above the strong floor and connected with a 1.5 inch bolt to the upturned channel cast into the wall, shown in Figure 4.4.



(a) Elevation of Loading Beam [14]



(b) Plan of Loading Beam [14]

Figure 4.4 – Cal Poly Wall Test Loading Beam

4.4 Axial Load Application

A constant axial load of 1.0%$A_g f'_c$ will be maintained throughout cyclic testing using a hydraulic jack on one side of the wall. Prestressing bars will connect the hydraulic jack, cyclic loading beam, and foundation as shown in Figure 4.5. Figure 4.6 shows the axial load actuator connection to the foundation. As load is applied by the hydraulic jack the balanced tension in the prestressing bars will pivot the beam and distribute the load evenly over the top of the specimen.

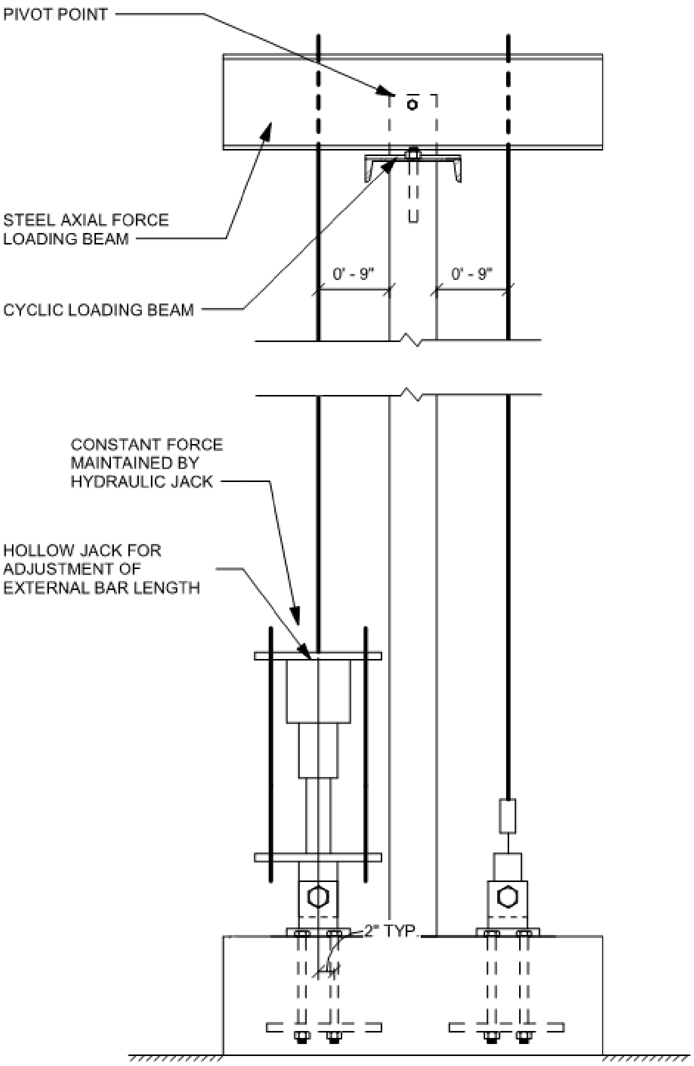


Figure 4.5 – Elevation of Axial Force Actuator [14]

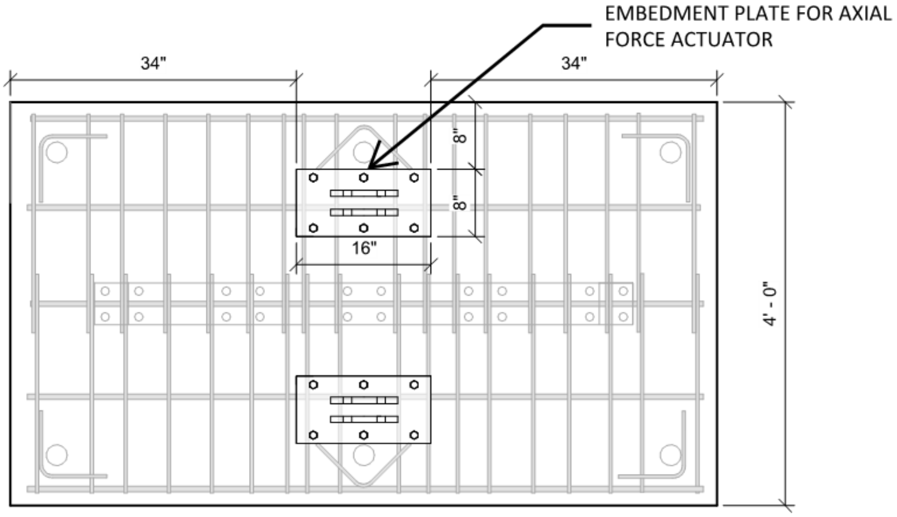
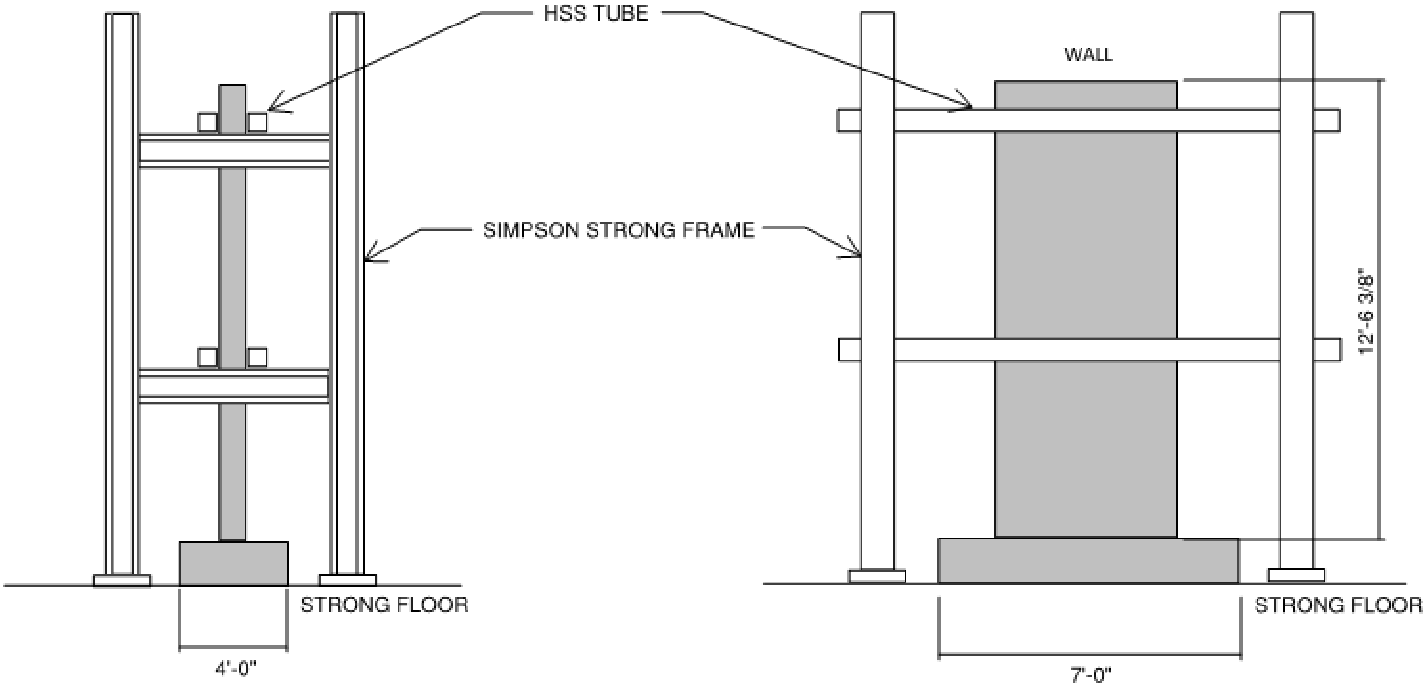


Figure 4.6 –Actuator Base Plate Embedment in Foundation [14]

4.5 Simpson Strong Frame

A steel strong frame, designed and fabricated by Simpson Strong Tie, is used to prevent out-of-plane movement of the wall specimen during testing. As shown in Figure 4.7 below, HSS tubes with Teflon pads are directly adjacent to the wall which act to prevent out-of-plane movement during the test. More detailed drawings of the Simpson Strong Frame can be found in Appendix A.5.



(a) (b)

Figure 4.7 – Elevations of Simpson Strong Frame

4.6 Reference Column

Isolated from the reaction frame loading setup, the reference column is a steel W-section bolted into the strong floor where displacement transducers will be attached to measure the absolute displacement of the wall specimen. Details of the reference column are shown in Figure 4.8.

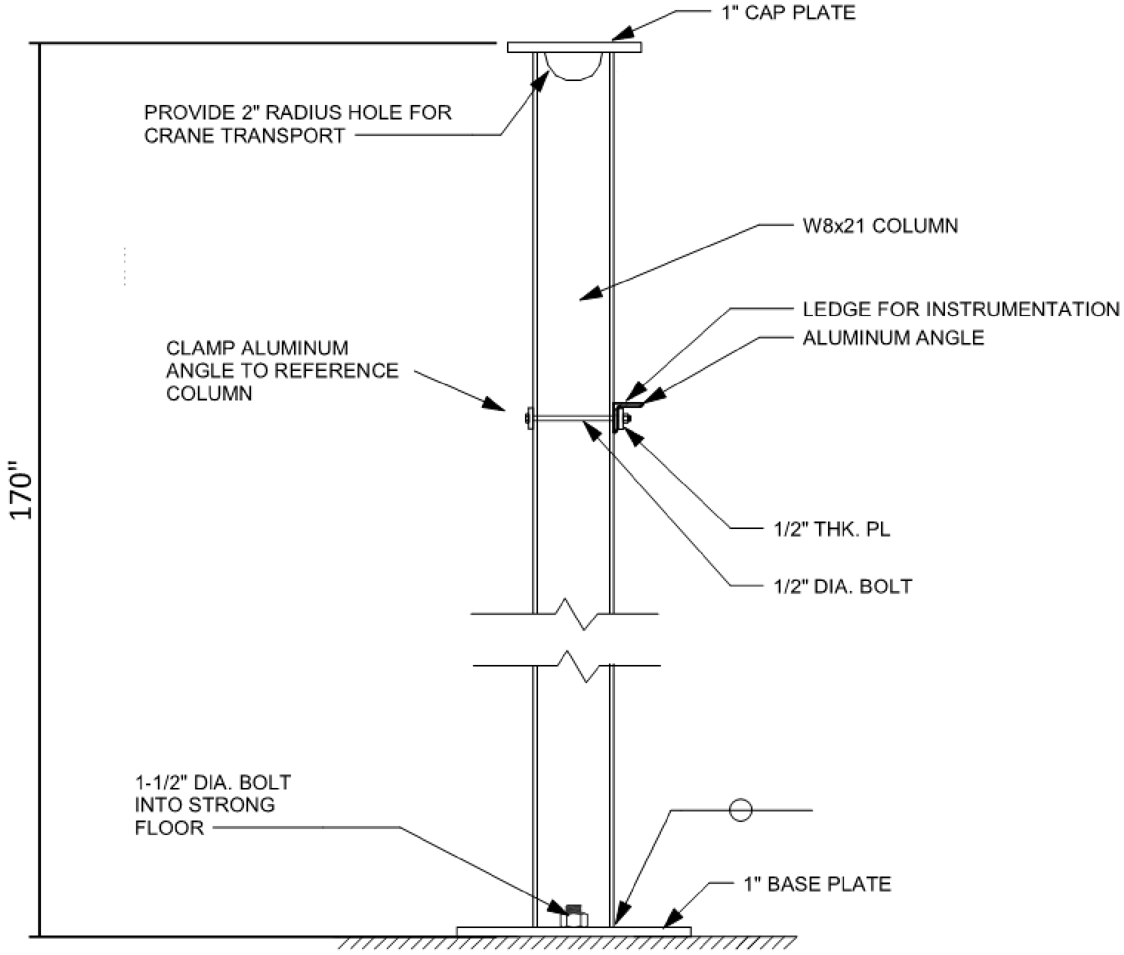


Figure 4.8 – Elevation of Reference Column [14]

5.0 Construction Sequence and Instrumentation

5.1 Construction

There will be a total of three pours for the foundation and two wall specimens. Construction will begin on the week of January 7, 2019 as described in detail in Sections 5.1.1 through 5.1.4.

5.1.1 Formwork

Formwork will be designed professionally by McClone Construction. The wall dictated a professional design as it is very slender with 12 feet of fluid pressure and a blow out in the forms would be highly detrimental to the experimental test program. It was decided that one lift for the whole height of the wall would be preferred as it allows for the forms to set and concrete testing to be conducted once. The team will acquire the lumber for the forms from local resources and the hardware will be provided by McClone to be picked up from their Sacramento, CA office.

5.1.2 Concrete

Concrete will be delivered by Cal Portland, and poured into a line pump with a 2.75 inch outside diameter hose which is the minimum hose size to pump 3/8 inch aggregate. This hose diameter would limit the wall thickness when accounting for cover concrete and vertical / horizontal reinforcement. However, the use of portholes in the side of the form allows for a pour with less than a 6 foot drop while maintaining a 5 inch wall thickness.

The 3 ksi mix consists of 3/8 inch pea gravel with an 8-9 inch slump for the wall and 6-7 inch slump for the foundation. The wall will require a high-slump concrete to allow for proper consolidation with minimal vibration for the 12 foot height. There will be open access to the foundation so there is no need for a high slump concrete. A self-consolidating mix was considered to avoid vibration, but was not selected as it is prone to leakage from formwork. Refer to Appendix A.3 for concrete mix details.

For each pour, a minimum of three concrete compression cylinders following ASTM C39 [6] and two modulus of rupture tests following ASTM C78 [5] will be conducted to obtain the strength of the concrete in the test specimen.

5.1.3 Steel Reinforcement

Steel reinforcement with a yield strength of 40 ksi for the foundation and wall will be supplied by LMS Reinforcing in Bakersfield, CA. LMS will provide a rebar cage for the foundation and loose #3 bars for the wall. It is desired to have loose bars for the wall because strain gauges will be applied to individual bars and assembled into the cage. Refer to Appendix A.3 for details on the steel mill specification.

5.1.4 Fiber Reinforced Polymer

The FRP consists of a carbon fiber sheet material combined with a resin which hardens and bonds to the concrete. Prior tests have indicated that FRP delaminates when used in long straight sections. To prevent delamination, FRP splay anchors will be inserted through the wall test specimen and splay over the FRP sheet on the exterior faces of the wall. Design of the FRP for the project will be completed by Fyfe. A brief manual describing installation of the FRP, based on a Fyfe training attended by the author in September 2018, is included in Appendix A.1.

5.2 Instrumentation

The instrumentation plan has not yet been finalized but will consist of three primary components:

- **Linear Variable Differential Transformers (LVDT)**: These LVDTs will be used at the base of the wall to measure base rotation and vertical/horizontal displacement.

- **String Potentiometers**: The string potentiometers will be placed along the height of the wall to measure the horizontal displacement of the wall (in and out of plane).

- **Strain Gauges**: Strain gauges will be used to measure strain in the rebar and on the concrete/ FRP surface. Strain gauges will be concentrated at the base of the wall to measure strain along the length of the plastic hinge region of the wall.

5.3 Construction Industry Application

This section compares the proposed FRP retrofit strategy with the current industry standard of epoxying rebar into and shotcreting an existing wall. This comparison will be a rough estimate of cost and schedule to retrofit one shear wall. Information on methods, cost, and schedule for epoxying and shotcreting was obtained from Bay Area Structural [16]. These values are based on their completed project retrofitting a 60 foot by 14 foot shear wall in Berkeley, CA, that included removing sheetrock to access the wall, epoxying rebar at two-thirds the depth of the wall, and applying 6-8 inches of shotcrete. The rebar was epoxied at 24 inches on center in each direction with vertical and horizontal rebar at 12 inches on center in each direction. The entire wall retrofit took 2-3 working days. Material and labor cost was roughly $30 per square foot. The following assumptions were made for the comparison:

- A base crew of 4 is assumed including a foreman, pump operator, and 2 finishers.
- A crew of 4 is assumed to take 3 days, where a crew of 6 could finish in 2.

Square Footage of Shotcrete = 60’x14’= 840 SF
Cost = (60’x14’)*$30 = $25,200
Schedule Impact Low = 3 Days for Crew of 4 Skilled Laborers
Schedule Impact High = 2 Days for Crew of 6 Skilled Laborers

Information on methods, cost, and schedule for applying FRP was obtained from Fyfe [22]. The process to apply the FRP includes removing sheetrock to access the wall, preparing the surface, mixing of resin, application of resin to FRP, and application of FRP to wall. An estimate of cost for FRP sheets is $20 per square foot per layer in material and labor. An estimate in cost for the anchors is $100 per anchor in material and labor. This cost is fully furnished cost including equipment, material, and time. The time for the sheets is roughly 30 square feet per man-hour. The time for the anchors is roughly 30 minutes per hole. This project could be completed with a crew of 2-4.

The following assumptions are made for the comparison:

- Wall thickness is 12 inches.
- 60 feet of shear walls is representative of two 30 foot long or three 20 foot long shear walls.
- The length of wall to be wrapped is based on the half-scale wall used in the Cal Poly wall test program with a boundary element length of 12-16 inches.
- The walls in this analysis have their ends exposed to apply FRP.
- 2-3 layers of FRP sheets are used.
- Anchors will be provided in 4 rows per boundary element, at 12 inches on center vertically.

Square Foot of Wrap Low = (2 Layers)*(2 Walls)*(2 Ends)*14’*(1’Back +1’Side+1’Front) = 336 SF
Square Foot of Wrap High = (3 Layers)*(3 Walls)*(2 Ends)*14’*(1.3’Back +1’Side+1.3’Front) = 907 SF
Number of Anchors Low = (4 rows)*(14’/1 Anchor per ft)*(2 Walls)*(2 Ends) = 224 Anchors
Number of Anchors High = (4 rows)*(14’/1 Anchor per ft)*(3 Walls)*(2 Ends) = 336 Anchors
Cost Low = (336 SF * $20/SF)+(224 Anchors * $100/Anchor) = $29,120
Cost High = (907 SF * $20/SF)+(336 Anchors * $100/Anchor) = $51,740
Schedule Low = ((336SF/30 per hour)+(224Anchors/3 per hour))/Crew of 4 = 21.5 Hrs = ~3 Days
Schedule High = ((907SF/30 per hour)+(336Anchors/3 per hour))/Crew of 2 = 71.2 Hrs = ~9 Days

When only considering these retrofit strategies on a wall, they have similar time impacts of 3 days with a crew of 4. The FRP is significantly higher in cost on a square foot of wall basis, regardless of whether the high or low cost is assumed. A significant cost that is not considered in this analysis for the shotcrete strategy are the slab and foundation upgrades necessary due to wall strengthening. Upgrade of the slabs and foundation requires demolition to access the bare structure and then a complete structural upgrade which drastically increases the cost and schedule impact during construction. The following outline the advantage and disadvantages of the FRP retrofit strategy:

Advantages

- Reduced cost and schedule
- FRP material is easily transported using man hoists on a jobsite, where shotcrete becomes difficult above the lower stories of a building.

Disadvantages

- The FRP is not a commonly used material in the construction industry as a structural repair, so it requires two days of training for laborers to be job ready. Although Fyfe provides this training free, that is two days of time where workers are paid and not being productive on a job.
- Shear walls are often located on the exterior of a building requiring significant demolition of exterior skin systems for the FRP to be wrapped on all sides of the boundary element.

The FRP retrofit strategy has promise, but will require a more in-depth assessment, from a construction standpoint, to be applicable. These concerns with constructability and cost are specifically why the Cal Poly research team has solicited advice from Fyfe.

6.0 Conclusions and Future Work

The final objective of this research project is to execute an experimental test program to determine the effectiveness of using FRP sheets and splay anchors to improve the ductility of pre 1980's RC shear walls. Thus far, the project team has designed the RC wall specimen, prepared the experimental test setup, and begun to order materials to construct the wall. Moving forward, the walls will be built, tested, and analyzed. If successful, this test program will be a step towards creating an effective retrofit strategy for existing non-code compliant concrete shear walls. The major milestones to complete the project by the end of the 2019 school year and begin disseminating results to the engineering community are listed below and the full schedule can be found in Appendix A.6:

- Completion of Design – 12/7/18
- Begin Construction of Foundation – 1/7/19
- Test Wall 1 – 3/4/19
- Test Wall 1 w/ FRP repair – 3/15/19
- Test Wall 2 w/ FRP retrofit - 5/20/19
- Completion of Conference Paper – 6/9/19

Based on the literature review presented in Section 2.0 of this report, the wall designed with FRP is expected to see increased ductility with minimal strength increase when compared with the wall having no FRP. To provide the evidence that justifies this hypothesis, the research team is focused on proper construction techniques and a well-developed instrumentation plan to acquire the necessary data. If successful, this retrofit strategy will provide a cost efficient and timely means to improve the safety of slender, non-ductile concrete buildings.

7.0 Acknowledgements

The following company representatives have and will continue to provide valuable industry support throughout the project. This includes material donations and knowledge from experience. Years of specialized experience from each party has allowed this project to take shape, and all the materials donated will allow the project team to complete the project.

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Joe Will and Bruce Mercier - CalPortland

Terry Roy and Quincy Dahm - McClone Construction

Kenny Gregoire - LMS Reinforcing

Scott Arnold, PE; Reymundo Ortiz; Victor Reyes, PE; Christian Molina - Fyfe

Emery Montague - Simpson Strong Tie

Kurt Stauss – Zircon

Ryan Stolz Pumping

David Kempken and Vince Pauschek – Cal Poly CAED Support Shop

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Architectural Engineering Department

Cal Poly Research, Scholarly and Creative Activities Grant

Structural Engineers Foundation Research Grant

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A. Appendix

A.1 FRP Installation Guide

A1.1 Important Notes Before Install

- The hardener is corrosive, do not make contact with skin and clean immediately. Refer to SDS for proper handling procedures.
- Ensure the temperature range is between 60-100 degrees. Increased temperature shortens the pot life (Pot life is the time where the resin is still workable).
- Humidity is problematic because the epoxy will never cure. If it is too humid Amine Blush will occur which is a hardness issue. A hardness tester can be used to ensure adequate hardness of material.
- Typical pot life is 3-4 hours. Operate under a 2 hour pot life assumption. Keep out of sunlight to extend the pot life.
- Mix ratio of resin is 100A:34.5B by weight or 100A:42B by volume. Always use a ratio based on weight if possible.
- Carbon fiber dust may cause electrical equipment to short. Do not use around electrical equipment.
- SCH 41 Carbon wrap is shipped in 2'x300' rolls which are 85 lbs and 0.04" thick.
- SCH 41(2x) Carbon wrap is shipped in 2'x 150' rolls which are 85 lbs and 0.08" thick. They will both use the same amount of epoxy.
- SHE 51A Glass wrap is shipped in 54"x150' rolls which are 155 lbs/roll.
- Part B of the epoxy will turn yellow with time.
- If Part A has crystals or is hazy, it has crystallized. Part B will not freeze. Part A must be reheated until completely clear before use.
- Scale should have an accuracy of two decimals.
- More epoxy is not better. Only use what is needed.

A.1.2 Preinstallation

1. Verify correct fabric type, orientation, number of layers, obstructions, and end details.
2. Perform all concrete repair.
3. Prepare work area.
4. Protect general surroundings.
5. Mark installation areas.

A.1.3 Mixing Tyfo S Epoxy – **Mix Ratio 100 A : 34.5 B**

1. Pour contents of Part B into Part A container.
2. Mix for 2-3 minutes using a industrial/commercial mixer (jiffy mixer) at a low RPM (400 RPM recommended). A low RPM is used to avoid air bubbles. Part A and B are clear before mixing. At the start of mixing the materials will be cloudy. When mixing is finished the epoxy should be clear again.
3. Pour the mixed epoxy into the B container.
4. Scrape the walls of the Part A Container to remove as much resin as possible. This step is important to ensure a proper ratio of Part A to Part B.

5. Remix the contents in the Part B container for 1-2 minutes at low RPM.
6. Once complete pour half the mixture back into the Part A container. The chemical reaction produces a large amount of heat as it approaches the end of its pot life. If the entire mixture is left in one container the epoxy can burn, cause damage, and create a safety hazard.

A.1.4 Mixing Tyfo S Thickened Epoxy

1. Mix a full kit of Tyfo S Epoxy (4 gallons).
2. Split the kit evenly into the A and B buckets (2 gallons each).
3. Fill remaining 3 gallons with cabosil TS-720 in each bucket. Rule of thumb: the remaining 3-gallon head space of a split kit is approximately 1.0 lb. of cabosil. The max amount allowed is 2.6 lbs. Half of the strength is lost when using 2 lbs of cabosil. If struggling to keep the fabric in place, it is suggested that cabosil is increased to 2.5 lbs. per kit (6.7% of weight).
4. Mix until completely mixed. Typically 4-5 minutes.
5. Scrape the edges of the bucket and remix for 1-2 minutes.
6. For small batches, add up to 5.4% by weight of the mixed epoxy.

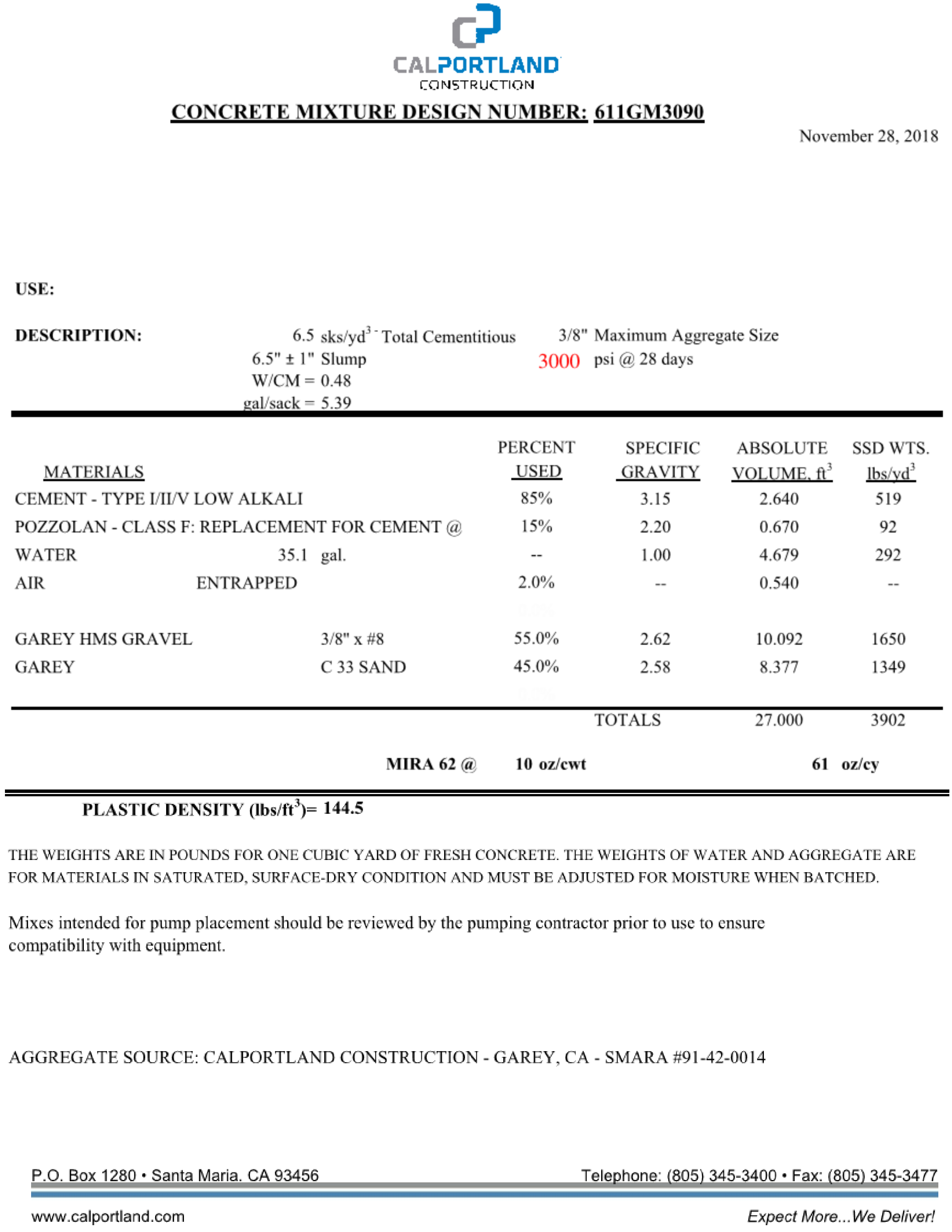
A.1.5 Manual Saturation Procedure (Wetout) – See install procedure before wetout.

1. Build saturation bath frame on a level surface. This bath should be made with a non-absorbing plastic sheet and it would be good to upturn the sides to avoid overspill. Make sure the plastic is attached to the ground securely to ensure ease of wet-out.
2. Place a dry fabric sheet into the bath and add Tyfo S Epoxy.
3. Work some of the epoxy into one side of the fabric until there are no dry spots. Use a trowel, roller, or similar to work the epoxy into the fabric. Apply pressure only in the direction of fiber.
4. Flip the sheet and coat the other side until the sheet is fully saturated.
5. Weigh a section of dry fabric.
6. Weigh an identical section of saturated fabric.
7. For carbon fabrics, a saturated piece should weigh twice the weight of the dry piece, +/- 10%.
8. For glass fabrics, a saturated piece should weigh 1.8x the weight of the dry piece, +/-10%.

A.1.6 Install Procedure

1. Prime the surface with Tyfo S Thickened Epoxy for a vertical wall, apply the fabric immediately.
2. Use thickened Tyfo S to:
    a. Fill voids and uneven surfaces
    b. Bond to vertical and overhead surfaces
    c. Install first layer of the saturated fabric.
    d. Protect fabric seams and edges.
    e. Seal fabric at the overlaps.
    f. Skim Coat
3. Use a trowel or roller to press the fabric into the Tyfo WS. Ensure that there are no air bubbles.
4. Add Tyfo WS between wraps, as required to keep fabric in place.
5. Install subsequent layers of fabric repeating this process.
6. Leave no more that a ½” gap between adjacent sections of fabric (butt splice).
7. Typical overlaps are 12” at all splice locations. Stagger splices to minimize buildup.
8. Apply a final coat of Tyfo WS to all seams and edges of the installed system.

A.2 Concrete Mix Design



CALPORTLAND
CONSTRUCTION

CONCRETE MIXTURE DESIGN NUMBER: 611GM3090

November 28, 2018

USE:

DESCRIPTION: 6.5 sks/yd³ - Total Cementitious 3/8" Maximum Aggregate Size
6.5" ± 1" Slump 3000 psi @ 28 days
W/CM = 0.48
gal/sack = 5.39

MATERIALS			PERCENT USED	SPECIFIC GRAVITY	ABSOLUTE VOLUME, ft³	SSD WTS. lbs/yd³
CEMENT - TYPE I/II/V LOW ALKALI			85%	3.15	2.640	519
POZZOLAN - CLASS F: REPLACEMENT FOR CEMENT @			15%	2.20	0.670	92
WATER	35.1	gal.	--	1.00	4.679	292
AIR	ENTRAPPED		2.0%	--	0.540	--
GAREY HMS GRAVEL	3/8" x #8		55.0%	2.62	10.092	1650
GAREY	C 33 SAND		45.0%	2.58	8.377	1349
				TOTALS	27.000	3902

MIRA 62 @ 10 oz/cwt 61 oz/cy

PLASTIC DENSITY (lbs/ft³)= 144.5

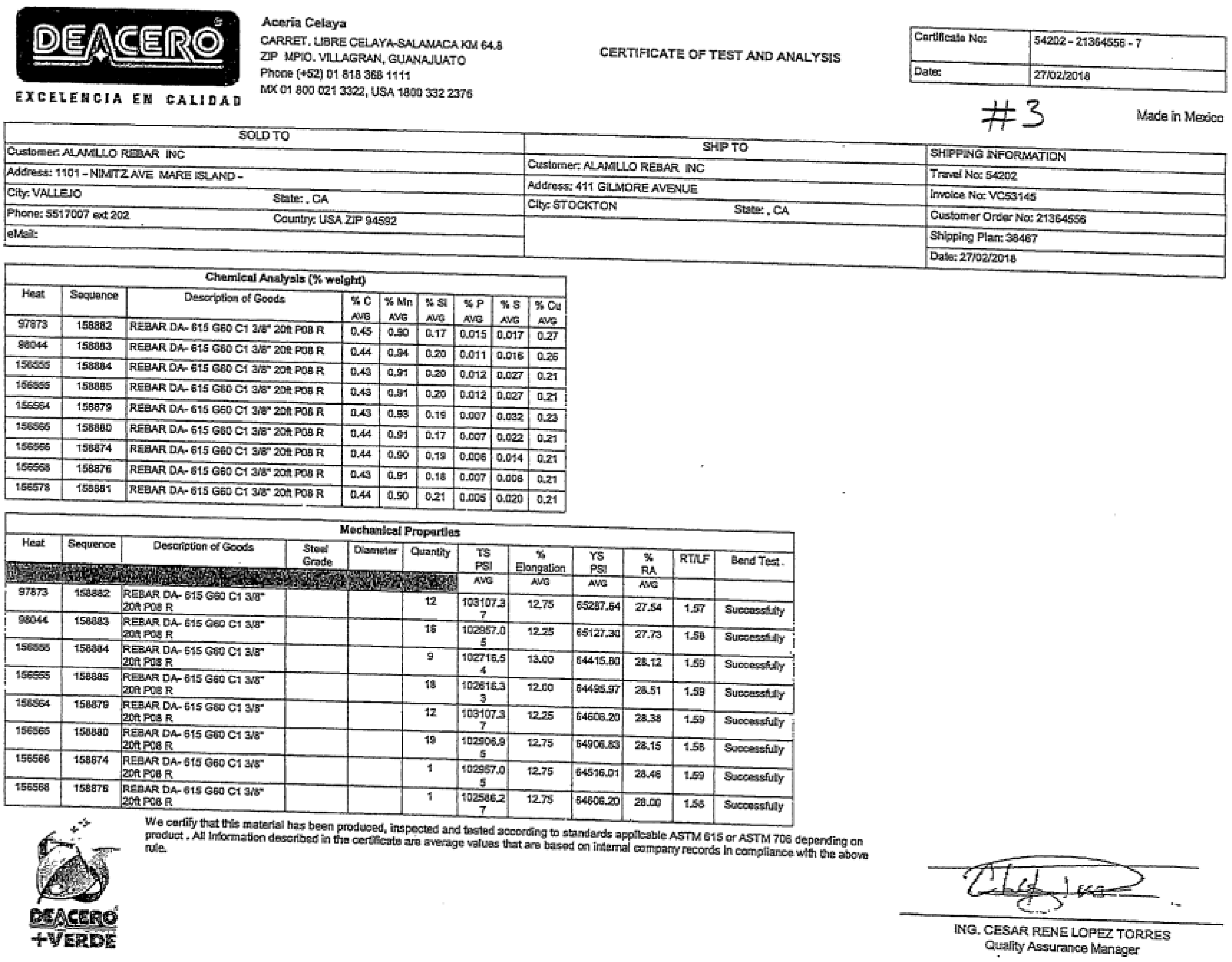
THE WEIGHTS ARE IN POUNDS FOR ONE CUBIC YARD OF FRESH CONCRETE. THE WEIGHTS OF WATER AND AGGREGATE ARE FOR MATERIALS IN SATURATED, SURFACE-DRY CONDITION AND MUST BE ADJUSTED FOR MOISTURE WHEN BATCHED.

Mixes intended for pump placement should be reviewed by the pumping contractor prior to use to ensure compatibility with equipment.

AGGREGATE SOURCE: CALPORTLAND CONSTRUCTION - GAREY, CA - SMARA #91-42-0014

P.O. Box 1280 • Santa Maria. CA 93456 Telephone: (805) 345-3400 • Fax: (805) 345-3477
www.calportland.com *Expect More...We Deliver!*

A.3 Steel Mill Certification



DEACERO

EXCELENCIA EN CALIDAD

Aceria Celaya
CARRET. LIBRE CELAYA-SALAMACA KM 64.8
ZIP MPIO. VILLAGRAN, GUANAJUATO
Phone (+52) 01 818 368 1111
MX 01 800 021 3322, USA 1800 332 2376

CERTIFICATE OF TEST AND ANALYSIS

Certificate No:	54202 - 21364556 - 7
Date:	27/02/2018

#3

Made in Mexico

SOLD TO
Customer: ALAMILLO REBAR INC
Address: 1101 - NIMITZ AVE MARE ISLAND -
City: VALLEJO State: , CA
Phone: 5517007 ext 202 Country: USA ZIP 94592
eMail:

SHIP TO
Customer: ALAMILLO REBAR INC
Address: 411 GILMORE AVENUE
City: STOCKTON State: , CA

SHIPPING INFORMATION
Travel No: 54202
Invoice No: VC53145
Customer Order No: 21364556
Shipping Plan: 38467
Date: 27/02/2018

Chemical Analysis (% weight)

Heat	Sequence	Description of Goods	% C AVG	% Mn AVG	% Si AVG	% P AVG	% S AVG	% Cu AVG
97873	158882	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.45	0.90	0.17	0.015	0.017	0.27
98044	158883	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.44	0.94	0.20	0.011	0.016	0.26
156555	158884	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.43	0.91	0.20	0.012	0.027	0.21
156555	158885	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.43	0.91	0.20	0.012	0.027	0.21
156564	158879	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.43	0.93	0.19	0.007	0.032	0.23
156565	158880	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.44	0.91	0.17	0.007	0.022	0.21
156566	158874	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.44	0.90	0.19	0.006	0.014	0.21
156568	158876	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.43	0.91	0.18	0.007	0.008	0.21
156578	158881	REBAR DA- 615 G60 C1 3/8" 20ft P08 R	0.44	0.90	0.21	0.006	0.020	0.21

Mechanical Properties

Heat	Sequence	Description of Goods	Steel Grade	Diameter	Quantity	TS PSI AVG	% Elongation AVG	YS PSI AVG	% RA AVG	RT/LF	Bend Test.
97873	158882	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			12	103107.37	12.75	65287.64	27.54	1.57	Successfully
98044	158883	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			16	102857.05	12.25	65127.30	27.73	1.58	Successfully
156555	158884	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			9	102716.54	13.00	64415.80	28.12	1.59	Successfully
156555	158885	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			18	102616.33	12.00	64495.97	28.51	1.59	Successfully
156564	158879	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			12	103107.37	12.25	64606.20	28.38	1.59	Successfully
156565	158880	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			19	102906.95	12.75	64906.83	28.15	1.58	Successfully
156566	158874	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			1	102957.05	12.75	64516.01	28.46	1.59	Successfully
156568	158876	REBAR DA- 615 G60 C1 3/8" 20ft P08 R			1	102586.27	12.75	64606.20	28.00	1.58	Successfully

We certify that this material has been produced, inspected and tested according to standards applicable ASTM 615 or ASTM 706 depending on product . All information described in the certificate are average values that are based on internal company records in compliance with the above rule.

DEACERO
+VERDE

ING. CESAR RENE LOPEZ TORRES
Quality Assurance Manager

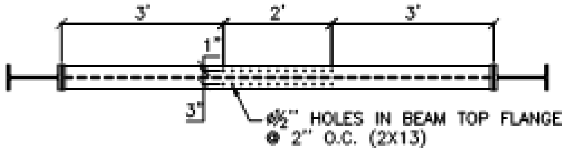
A.4 Details of Parametric Study to Finalize Wall Design

fy= 50ksi, fc'=4.5ksi, Pu=0.025*fc'*Ag														
	Specimen	Height (ft)	Length (in)	Thickness (in)	Shear Span	(CSAR)	Pu (kip)	Vert Rebar	Single Mat or Double Mat	As (in^2)	Horiz Rebar	c (in)	Mpr (kip-ft)	Vu (kips)
Group A - H=12', Thickness = 6", Variable = L	A -1	12	62.025	6	2.32	10.34	41.87	No. 3 @ 19.8" o.c.	Double	0.88	No. 3 @ 14.3" o.c.	3.42	212.07	17.67
	A - 2	12	42.2251	6	3.41	7.04	28.50	No. 3 @ 19.8" o.c.	Double	0.66	No. 3 @ 14.3" o.c.	2.28	102.84	8.57
Group B - L = 62.025," Thickness = 6" Variable = H	B -1	13	62.025	6	2.52	10.34	41.87	No. 3 @ 19.8" o.c.	Double	0.88	No. 3 @ 14.3" o.c.	3.42	212.07	16.31
	B - 2	12	62.025	6	2.32	10.34	41.87	No. 3 @ 19.8" o.c.	Double	0.88	No. 3 @ 14.3" o.c.	3.42	212.07	17.67
Group C - H = 12', L = 56", Variable =	C - 1	12	62.025	6	2.32	10.34	41.87	No. 3 @ 19.8" o.c.	Double	0.88	No. 3 @ 14.3" o.c.	3.42	212.07	17.67
	C - 2	12	62.025	5	2.32	12.41	34.89	No. 3 @ 19.8" o.c.	Double	0.88	No. 3 @ 17.6" o.c.	3.66	194.34	16.20
	C - 3	12	55.425	4	2.60	13.86	24.94	No. 3 @ 17.6" o.c.	Single	0.44	No. 3 @ 11" o.c.	3.79	150.76	12.56

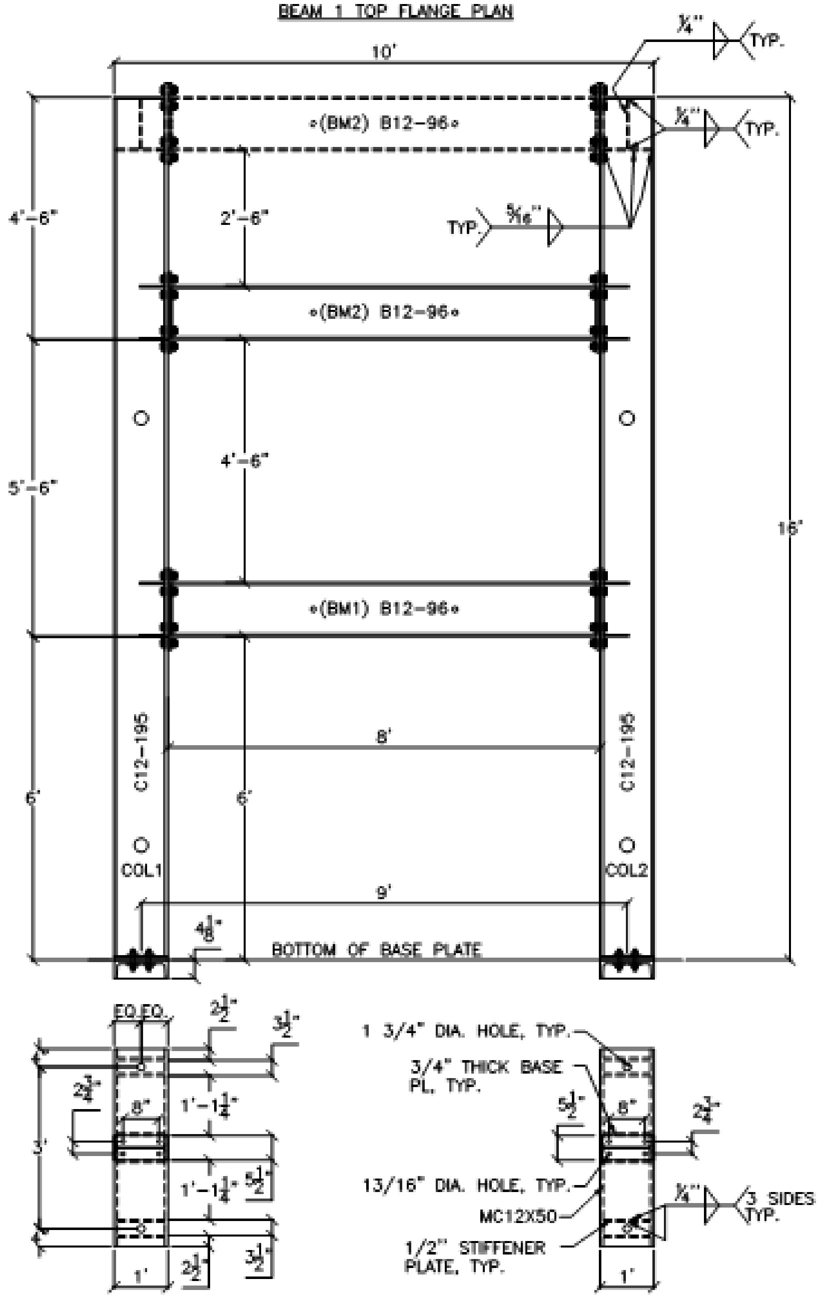
fy= 60ksi, fc'=3.5ksi, Vu=30kips, Pu=0.05*fc'*Ag								
	Specimen	Height (ft)	Length (ft)	Thickness (in)	Aspect Ratio	Cross-Sectional Aspect Ratio	Pu (kip) (5%fc'Ag)	Mu (kip-ft) (To base of ftg. +1')
Group A - H=12', L=4.8'	A-1	12	4.8	12	2.50	4.8	103.68	195
	A-2	12	4.8	10	2.50	5.76	86.4	195
	A-3	12	4.8	8	2.50	7.2	69.12	195
	A-4	12	4.8	6	2.50	9.6	51.84	195
Group B - H=12', L=4'	B-1	12	4	12	3.00	4	86.4	195
	B-2	12	4	10	3.00	4.8	72	195
	B-3	12	4	8	3.00	6	57.6	195
	B-4	12	4	6	3.00	8	43.2	195
Group C - H=11', L=4.4'	C-1	11	4.4	12	2.50	4.4	95.04	180
	C-2	11	4.4	10	2.50	5.28	79.2	180
	C-3	11	4.4	8	2.50	6.6	63.36	180
	C-4	11	4.4	6	2.50	8.8	47.52	180
Group D - H=11', L=3.67'	D-1	11	3.67	12	3.00	3.67	79.272	180
	D-2	11	3.67	10	3.00	4.404	66.06	180
	D-3	11	3.67	8	3.00	5.505	52.848	180
	D-4	11	3.67	6	3.00	7.34	39.636	180
Group E - H=10', L=4'	E-1	10	4	12	2.50	4	86.4	165
	E-2	10	4	10	2.50	4.8	72	165
	E-3	10	4	8	2.50	6	57.6	165
	E-4	10	4	6	2.50	8	43.2	165
Group F - H=10', L=3.3'	F-1	10	3.3	12	3.03	3.3	71.28	165
	F-2	10	3.3	10	3.03	3.96	59.4	165
	F-3	10	3.3	8	3.03	4.95	47.52	165
	F-4	10	3.3	6	3.03	6.6	35.64	165
Group G - H=9', L=3.5	G-1	9	3.5	12	2.57	3.5	75.6	150
	G-2	9	3.5	10	2.57	4.2	63	150
	G-3	9	3.5	8	2.57	5.25	50.4	150
	G-4	9	3.5	6	2.57	7	37.8	150

fy= 60ksi, fc'=4ksi, Vu=30kips, Pu=0.05*fc'*Ag								
	Specimen	Height (ft)	Length (ft)	Thickness (in)	Aspect Ratio	Cross-Sectional Aspect Ratio	Pu (kip) (5%fc'Ag)	Mu (kip-ft) (To base of ftg. +1')
Group A - H=12', L=4.8'	A-1	12	4.8	12	2.50	4.8	103.68	195
	A-2	12	4.8	10	2.50	5.76	86.4	195
	A-3	12	4.8	8	2.50	7.2	69.12	195
	A-4	12	4.8	6	2.50	9.6	51.84	195
Group B - H=12', L=4'	B-1	12	4	12	3.00	4	86.4	195
	B-2	12	4	10	3.00	4.8	72	195
	B-3	12	4	8	3.00	6	57.6	195
	B-4	12	4	6	3.00	8	43.2	195
Group C - H=11', L=4.4'	C-1	11	4.4	12	2.50	4.4	95.04	180
	C-2	11	4.4	10	2.50	5.28	79.2	180
	C-3	11	4.4	8	2.50	6.6	63.36	180
	C-4	11	4.4	6	2.50	8.8	47.52	180
Group D - H=11', L=3.67'	D-1	11	3.67	12	3.00	3.67	79.272	180
	D-2	11	3.67	10	3.00	4.404	66.06	180
	D-3	11	3.67	8	3.00	5.505	52.848	180
	D-4	11	3.67	6	3.00	7.34	39.636	180
Group E - H=10', L=4'	E-1	10	4	12	2.50	4	86.4	165
	E-2	10	4	10	2.50	4.8	72	165
	E-3	10	4	8	2.50	6	57.6	165
	E-4	10	4	6	2.50	8	43.2	165
Group F - H=10', L=3.3'	F-1	10	3.3	12	3.03	3.3	71.28	165
	F-2	10	3.3	10	3.03	3.96	59.4	165
	F-3	10	3.3	8	3.03	4.95	47.52	165
	F-4	10	3.3	6	3.03	6.6	35.64	165
Group G - H=9', L=3.5	G-1	9	3.5	12	2.57	3.5	75.6	150
	G-2	9	3.5	10	2.57	4.2	63	150
	G-3	9	3.5	8	2.57	5.25	50.4	150
	G-4	9	3.5	6	2.57	7	37.8	150

A.5 Simpson Strong Frame Plans



BEAM 1 TOP FLANGE PLAN

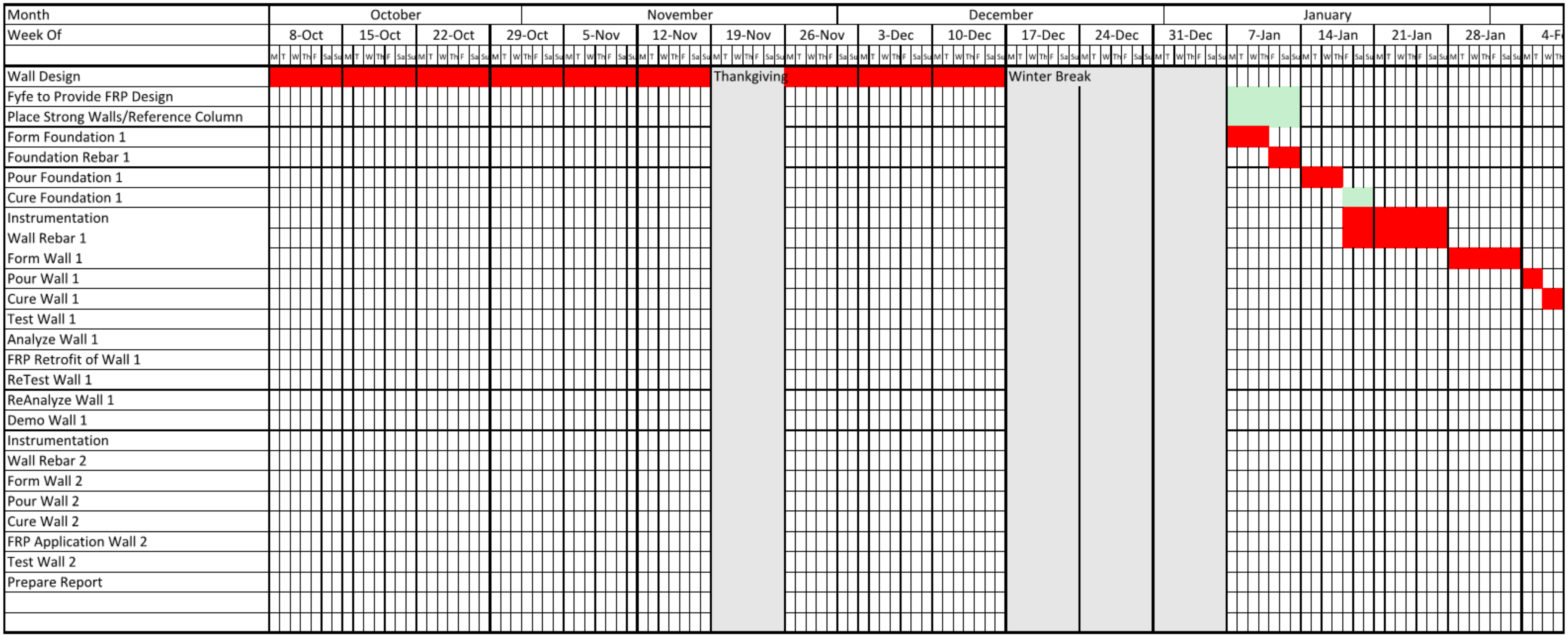


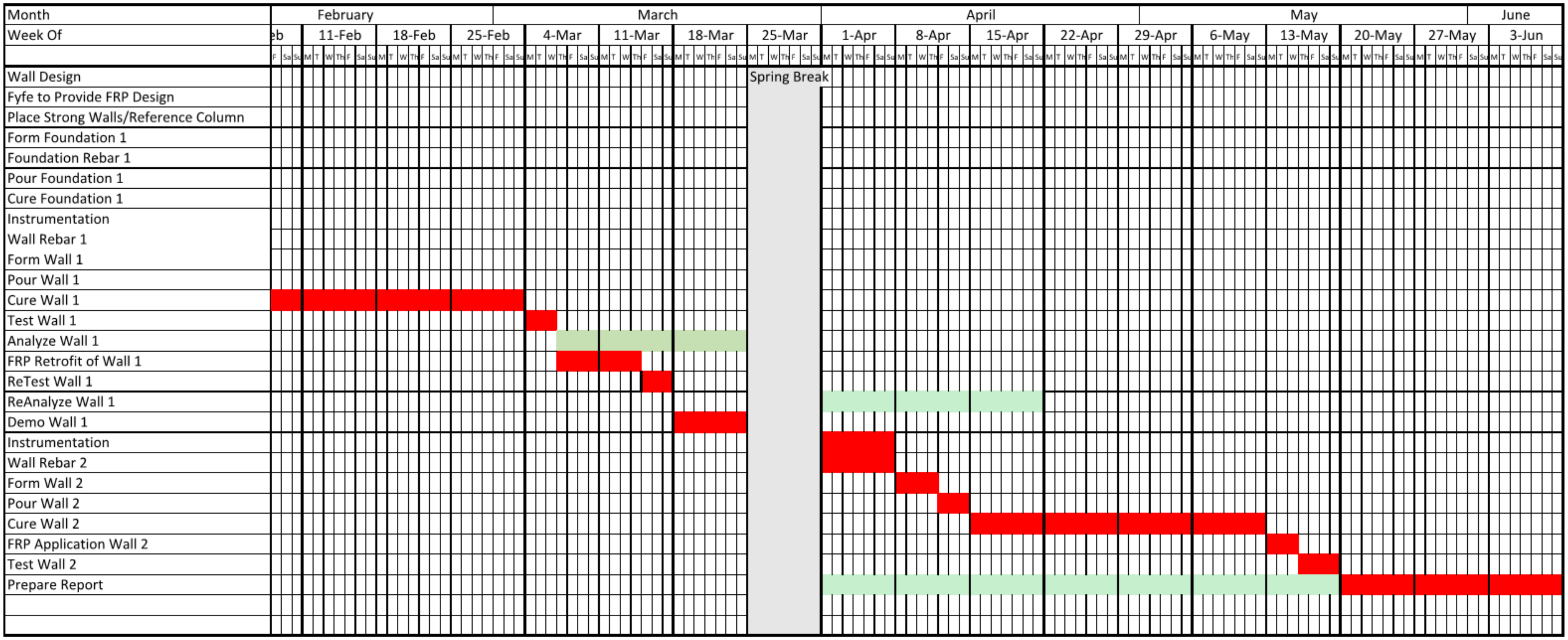
TOP VIEW

SCALE:3/4" = 1'-0"

A.6 Cal Poly Wall Test Program Schedule

Red indicates the critical path of the project. Green are items which have float indicating items which can be delayed without delaying the overall schedule.





Month	February				March				April					May				June
Week Of	eb	11-Feb	18-Feb	25-Feb	4-Mar	11-Mar	18-Mar	25-Mar	1-Apr	8-Apr	15-Apr	22-Apr	29-Apr	6-May	13-May	20-May	27-May	3-Jun
Wall Design								Spring Break										
Fyfe to Provide FRP Design																		
Place Strong Walls/Reference Column																		
Form Foundation 1																		
Foundation Rebar 1																		
Pour Foundation 1																		
Cure Foundation 1																		
Instrumentation																		
Wall Rebar 1																		
Form Wall 1																		
Pour Wall 1																		
Cure Wall 1	🟥	🟥	🟥	🟥														
Test Wall 1					🟥													
Analyze Wall 1					🟩	🟩	🟩											
FRP Retrofit of Wall 1					🟥	🟥												
ReTest Wall 1						🟥												
ReAnalyze Wall 1									🟩	🟩	🟩							
Demo Wall 1							🟥											
Instrumentation									🟥									
Wall Rebar 2									🟥									
Form Wall 2										🟥								
Pour Wall 2										🟥								
Cure Wall 2											🟥	🟥	🟥	🟥				
FRP Application Wall 2															🟥			
Test Wall 2															🟥			
Prepare Report									🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥