Construction of Modular Concrete Footings for Use in Cal Poly’s High Bay Laboratory

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This project-based senior project had the end goal of creating two concrete modular foundations that can be used in the High Bay Laboratory for testing procedures. The concrete modular blocks are 6’ long by 3’ wide, and 1.5’ tall. The foundations each held 100 embeds. Each embed serves as an anchor point for various attachments for testing purposes. This was an interdisciplinary project amongst two CM students and one ARCE student. The ARCE student was responsible for the design of the blocks, encompassing the formwork and the rebar. The CM students were responsible for estimating, scheduling, and the construction of the blocks. Construction of the two footings involved the fabrication of plywood box forms that eventually held the rebar cage and various embeds. Additional reinforcement was needed on the outside of the box forms to allow for the forms to be strong enough to withstand the outward pressure of the wet concrete as it was poured into each of the boxes. The completed modular foundations were stripped of the plywood formwork and inverted to be the proper orientation when bolted into the High Bay Lab floor.

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Background

While performing several interviews with various professionals in the construction industry as part of the CM 460 course, an alumnus who graduated a few years prior had mentioned the project-based senior project he intended on completing before the COVID pandemic had prevented the physical deliverables to be constructed. His plan was to pour a concrete shear wall to be broken to test the benefits of Fiber Reinforced Polymer. The testing portion of the project was ultimately serving to benefit the ARCE department. Although this was not the exact project that was chosen, it sparked the idea to work interdisciplinary with the ARCE department to improve the capacity of the High Bay Laboratory. Specifically, the plan was to replicate two existing modular foundations that were positioned in the High Bay for stress testing. With the construction and implementation of two more of these modular foundation blocks, the surface area of accessible anchor points could be drastically increased, allowing for more testing procedures to take place.

Preconstruction

While the ARCE student involved with this project was working on eliminating any kinks in the design that may have been found in the construction of the first modular foundation block, the Construction Management team worked on creating both a schedule and budget to plan out the quarter accordingly. Primavera P6, a scheduling
software, was used in conjunction with a Material Takeoff Sheet to create these deliverables. The next step was to submit a grant request to receive sufficient funding necessary for procuring the materials. By utilizing both the schedule and budget, the entirety of construction process could be accurately outlined, giving the grant foundation precise documentation entailing what their funding was to be used toward. A total of $3,805.41 was requested for the approximate 6 weeks of construction activities. Although the grant request was ultimately accepted, the funds could not be utilized for the construction project. Due to extraneous circumstances involving the CM Department, alternate methods of funding for the procurement of the materials were to be obtained. Luckily, a couple of sponsors within the construction industry came to the rescue. Cal Portland donated all the high-strength concrete for the project and delivered a truck in accordance with the mix design and scheduled pour date. Additionally, Simpson Strong-Tie was able to provide the necessary embeds for the foundation blocks, which amounted to 200 in total. Several preliminary meetings between the Construction Management and ARCE departments were held to ensure the proper materials were procured as well as the constructability of the project. Once the materials were picked up and set aside in the designated lay-down area in the SST building, the construction process was ready to proceed.

**Construction**

The first step in constructing the modular foundations was to cut the plywood formwork panels into the proper dimensions. The student from the ARCE department had designed an AutoCAD file that could be read by a CNC Router in the CAED workshop on campus. With this machine shown in Figure 1, the formwork panels could be created with extreme precision. The file was read by the computer, which instructed which attachment to fix onto the universal arm of the machine. It would then track across the surface of the plywood, making cuts and drilling holes in the locations previously determined by the ARCE student.

![Figure 1. CNC Router](image-url)
This machine was even capable of pre-drilling the screw holes, which drastically simplified the next step. Additionally, the machine cut a dado into the base panel of the formwork, allowing the four vertical panels to be lined up easily and screwed together to create a sturdy and plum box form, as shown in Figure 2. Triangular pieces were then screwed into the corners of all the conjoined faces to allow for all the edges to be beveled.

![Empty Plywood Box Form](image)

Figure 2. Empty Plywood Box Form

Once the plywood box forms were finished, it was time to fasten the rebar in junction with couplers positioned on the inside of the boxes at every hole. On the outside, bolts were screwed into the couplers to anchor the embeds to the formwork. Nuts and washer plates were then screwed onto the end of each bar to ensure adequate anchorage into the concrete that will eventually be poured into the box. Additional rebar was then tied into the box, creating a very intricate cage of steel to increase the tensile strength of the concrete foundations. As more and more bars were inserted into the confined space of the plywood box form, it became increasingly difficult to position the and tie the bars together. There was a large learning curve in the beginning, and the order of placement of the bars needed to be shuffled around several times to ensure that every bar could be inserted and tied accordingly. The quantity of bolts that we had procured to fasten the rebar to the formwork turned out to be insufficient, so the transverse rebar running the lengths of each box needed to be fastened with an alternate method. The decision was made to use the scrap pieces of rebar that had been cut off the manufactured length and fastened into the outside of the coupler. Then, the final pieces to be inserted into the form boxes were the PVC tubes. This proved to be an extremely difficult process, as most of the void space within the box had been replaced by rebar, as shown in Figure 3. Luckily, with the precise AutoCAD model created by the ARCE student, the holes cut into the formwork panels were in the correct location with little to no buffer. The tubes had to be shimmied in through the sides inch by inch with several locations needing rebar to be pulled or pushed to allow the PVC to slide by.
The final step to take to prepare the formwork before pouring concrete was to reinforce the outside perimeter of the plywood box. This was accomplished with 2x4’s that were strategically placed throughout the protruding bars. Due to the liquidity of the concrete, outward pressure increases as the volume of the concrete increases. This turned out to be a more time-consuming process than initially thought, mostly due to all the precise cuts of the 2x4’s along with all the fastening of the nuts, which could not be hand-tightened, requiring multiple wrenches instead. The completed box forms are shown in Figure 4, stationed in the High Bay Lab for the concrete truck.
With the Plywood Box Forms finished, the next step was to pour the concrete. CalPortland was scheduled to deliver a truck and the boxes were prepared for the pour. The two boxes were completed in a convenient location, just inside the High Bay’s entry doors, which allowed for the concrete truck to back up right against them. The High Bay courtyard was shared with several other projects that required real estate in this space, so extensive coordination was required to safely maneuver the back end of the truck within proximity of the box forms. The driver came out to extend the chute and then began to angle the hopper toward the front sides of the box forms. Multiple shovels and a vibrator were used to place the concrete throughout all the voids in the rebar cages, as shown in Figure 5. It was crucial to vibrate the concrete as it was placed into the forms since there were so much steel and PVC obstructing the chute from placing the concrete down into the bottom of the forms. As the rebar cage filled with concrete, it became increasingly difficult to remember where the voids were to insert the vibrator and access the low and narrow points in the box forms that were the hardest to access and allow concrete to fill.

![Figure 5. Concrete Pour](image)

Once the boxes were completely poured, the next step was to finish the top layer by screeding a wooden board across the top edges of the box forms. This was so that the surface would be smooth and level, which was important because these foundations were to be flipped 180° so that the surface poured against the base of the box form would be the top face. With the vertical PVC tubing running vertically inside the rebar cage and protruding out of the form, it was necessary to cut them as close to the same elevation of the top of box form edge as possible. This was to allow the wooden board to move across the box with one pull. Along the perimeter, a trowel was used to protect the corners from cracking in transportation.
With both boxes poured, the final step was to strip the formwork and inspect the quality of the foundations. This was an extensive process, as all the formwork reinforcement had to be stripped, board by board, each requiring wrenches and crowbars to effectively separate them from the concrete surface, as shown in Figure 6.

![Figure 6. Process of Stripping Formwork](image)

The two blocks were then inverted with the use of a forklift, as shown in Figure 7, so that the bottom layer of bolts was revealed, and the final layer of formwork could be removed. It was at this moment, that the realization was made that the duct-tape cover that had been applied to the top of the PVC openings had failed. Overflow of the concrete had leaked into the openings of the tubes and eventually cured to the inside. An additional procedure was now required to chip out the concrete to reveal the voids that are essential to the foundations’ functionality.

![Figure 7. Inverted Foundation Block](image)

After the PVC tubes were chipped to be free of concrete, they were shaved down to be flush with the concrete surface. The two foundations were now smooth blocks and ready to be transported to the inside of the high bay lab where there were to be fastened to the floor with anchor bolts. It was at this moment, that the realization was made that when the PVC tubes collected the overflow of concrete, the wood board and trowel used to finish the concrete had bumped into the top edge of the tubes and knocked them askew. This flaw in the construction process turned out to have a large impact on the useability of these foundation blocks. Fortunately, only two of the PVC tubes had substantially shifted, which prevented the anchor bolts from lining up with the holes in the high bay floor. Additional chipping of concrete was needed to align the voids in the blocks to the hole in the floor.
Deliverables
With all this work completed, the construction process to build these two blocks had proven to be successful. Matching the specifications and meeting the needs of the ARCE student who was using them for his master’s thesis was the top priority throughout the entirety of the quarter. This became quite a challenge with one hundred embeds in total – seventy-two located on the top surface and twenty-eight distributed throughout the four vertical sides. As if this was not enough for complexity, the rebar cage, PVC tubes, and additional formwork to create the beveled edges made for an extremely crammed box to fill with concrete. After inspection of both completed foundation blocks, shown in Figure 8, it appeared that the efforts made to vibrate out all the voids in the concrete had paid off.

Figure 8. Completed Foundation Block

The final step in completing the demands of the ARCE department was to conduct cylinder testing on the four concrete cylinders that were poured in the same batch as the two footings. Tests were scheduled for 7, 14, 21, and 28 days after the concrete pour took place. Using a machine in the High Bay Lab, a compressional force was applied to each of the cylinders and the maximum force exerted was noted for each cylinder. Throughout the testing of the concrete cylinders, it was determined that the cylinders were not meeting the expected strength. Because the mix of concrete was received from Cal Portland and delivered in a truck, it seems that the cylinders were poured improperly, and that this was the reason for the tests to differ from the expected results. The manner in which each of the cylinders had fractured was the most apparent sign that the cylinders had not been poured correctly.

For a standard concrete cylinder, there are several different types of fractures that are expected to have the possibility of taking place; however, the image above of the last cylinder broken on day 28 shows a type of fracture that is not in the standard types of cylinder fractures, as shown in Figure 9.
Lessons Learned & Conclusion

Several valuable lessons were learned throughout the planning and construction process, most of which relate to improving future iterations of additional footings. Since the blocks are modular, they can be arranged in a multitude of orientations to accommodate the extensive tests that are planned to be conducted. With the implementation of additional modules, the foundation system will become more capable of supporting larger and more complex testing. Regarding the overall constructability of the block, there were no issues in the design that needed to be revised, so they met all the specifications and requirements.

Multiple obstacles arose during this senior project, which were the times where the most learning occurred. The first item that gave struggle in construction was the arrangement of rebar inside of the plywood box forms. Several attempts were made to successfully place every necessary bar inside of the cage, which needed to be done in a certain order and pieces of the box form had to be disassembled to allow for bars to be inserted. Working as a team was crucial for this to be successful, as certain bars needed to be pulled or pushed slightly to allow for perpendicular ones to slide past. The next obstacle that occurred when we poured the concrete was the overflow that fell into the voids of the PVC tubes. Chipping this out after the fact was an extremely time consuming and tedious task that could have been avoided if things were done differently. One solution would be to create a more durable barrier than duct tape to cap the void of the PVC. Another would be to leave length on the vertical PVC tubes so that the top edges are above the top of the box forms. Although this would eliminate the overflow of concrete into the voids, screeding the concrete would require additional coordination. This solution proved to be the best when overcoming the next roadblock. Since two of the PVC tubes were knocked out of plum in the concrete pour, additional concrete chipping was needed. If the tubes were kept at their longer lengths, then additional efforts could have been made to keep them plum. For instance, a top template could be used to prevent the tubes from moving during the pour. Whatever method is used, the PVC tubes would most likely need to be longer than the box form itself to anchor the tube at both sides. While the last obstacle faced has an easy remedy, the results are extremely significant. If proper procedures were taken to pour the concrete cylinders with the footings, then there would be more reliable data to understand the overall strength of the concrete. To improve the concrete pour, there should be a specific role taken to complete the test cylinders according to the ASTM standards. Additional cylinders would also be advisable in case there are complications in the strength testing.