Teaching Constructability Using Third-World Constraints

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Abstract

Given the ever-expanding technical requirements for producing a proficient bachelor of civil engineering, departments need to develop innovative courses that incorporate aspects of many civil disciplines not otherwise covered within the curriculum. Students are not often asked to consider design, construction, architectural, material, and economic issues in combination, yet they must be proficient at handling these issues in order to be successful in their professional careers. In the spring semester of 2000 the Department of Civil and Environmental Engineering at Villanova University initiated a structural engineering capstone design course that brings to focus the role of structural engineers in a global context, highlighted by structural design and construction in a third world country. The initial project involved the design and construction of a 25 foot tall reinforced concrete cross for a Catholic orphanage in Posas Verdes, Honduras. The project was challenging due to many constraints and limitations such as time, third world conditions, communication, material quality and availability, and other construction issues. Presented herein is a description of the cross project, the course format, and the associated engineering and construction challenges.

Introduction

Villanova University is an independent coeducational institution of higher learning founded by the Augustinian Order of the Roman Catholic Church. A medium-sized Catholic institution and comprehensive university, Villanova emphasizes undergraduate instruction and is committed to a strong liberal arts component in each of its undergraduate programs, including engineering (Villanova, 1979). Furthermore, the University has always encouraged and supported its faculty, students, and staff in providing public service to the community. Ultimately, all of these programs and support are seen as a means of developing a well-rounded student.

The mission of the Department of Civil and Environmental Engineering is to provide students with a high quality, contemporary, broad-based, civil engineering education within the context the Judaeo Christian mission of the University. The department offers multiple courses in five specialty areas of civil engineering: environmental, geotechnical, structural, transportation, and water resources. Given a resource of twelve full-time faculty, it is challenging to incorporate other civil engineering specialties such as materials or construction, especially in a manner that demonstrates practical application of the subjects.

The objective of any engineering capstone design course should be to mesh the technical knowledge of the discipline with an encompassing engineering problem that incorporates "real world" issues and challenges. The primary role of a civil engineer is to serve the community; thus, it is essential that students understand the impact of engineering projects on, and the context of engineering projects within, society. With all of the aforementioned criteria in mind, the objective of the structural capstone course described herein is to tie together technical (structural, materials, and construction) and humanistic issues through a challenging real world project. This paper focuses on the constructability issues of the project and is divided into the following sections: project development, course description, design and construction challenges, project construction, outcomes, and continuing work.

Project Development

One of the poorest countries in the Western Hemisphere, Honduras is a country still trying to recover from recent guerilla wars and has an overwhelming number of children whose parents are unable to provide for them. Amigos de Jesus (Friends of Jesus), a Catholic orphanage, offers a refuge for abandoned and abused boys. The orphanage was co-founded in 1998 by Sister Teresita, S.S.N.D., a Honduran nun, Reverend Dennis O' Donnell, rector of the Malvern Retreat House in Malvern, PA, and Anthony and Christine Granese, a 1990 Villanova Civil Engineering alumnus and his wife. The mission of the orphanage is to provide boys the opportunity to grow-up in a loving environment where they will receive a formal education and a lifelong skill such as farming, welding, or carpentry. In late December 1999, Anthony Granese approached the College of Engineering with the idea of developing a relationship with the orphanage.

At that time, work on a two-story reinforced concrete structure to house the children and the administrators of the orphanage was almost complete, and construction of a second similar structure had been initiated. The design of another building for the orphanage, while within the scope of a capstone course, did not meet the current needs of the orphanage. At the initial meeting the idea of building a cross on a hill overlooking the orphanage was discussed. The cross would serve as a symbol of hope for the boys and the surrounding villages in the valley. The selection of this project in a third world country would offer the students some interesting design challenges, tie directly to the University's Catholic mission, and provide the feasibility of being constructed in one week. Consequently, plans were made to focus the course around the design and construction of a 25-foot tall reinforced concrete cross.

Course Description

The capstone course is allotted three hours per week, and utilizes a team-based approach for problem solving. The course was initiated by introducing the project and receiving feedback from the students on their interests and possible participation in the construction of the cross in Honduras over spring break. The seven students enrolled in the course were excited by the project and four students immediately volunteered to go to Honduras in lieu of going on their senior year spring break. The students were divided into two design groups with two students from each group going on the trip. The course was set up such that there were seven additional meetings of the class prior to the trip. Class lectures included development of a concrete mix design, use of structural design codes, foundation design, and formwork design (topics not covered in their introductory structural design course).

Design and Construction Constraints

The first task was to develop project and construction schedules based on the dates of the trip and a five-day work week in Honduras. In order to develop the construction schedule the students were given a fixed end date for the final concrete pour. The groups compiled a list of questions to be sent to the site asking about materials, equipment, site conditions, and cross dimensions. The orphanage did not have a phone line, and checked email offsite approximately twice a week. Students proceeded with the work relying on design assumptions while waiting for clarification from the site. From the answers to their inquiries they were able to further define the project constraints.

The orphanage specified the dimensions of the cross. It was to be 22 ft tall, supported by a 30 in by 20 in column with a cross beam that would be 30 in deep x 20 in deep and 11.5 ft long. The rebar available to the students ranged between ¼ in and ¾ in diameter bars. Thirty-six, ¾ in and twenty-two, 5/8 in bars with thirty-foot lengths were available on site. The site requested that these bars be utilized in lieu of ordering additional steel. Other sizes and lengths could be obtained, if absolutely necessary, but this was not a desirable alternative. Plywood and lumber was difficult to obtain and very expensive; consequently, almost all wood used for formwork or scaffolding would need to be hand cut from trees on site. Sheet metal and small angle was available and the orphanage had welding capabilities.

For mixing concrete, Portland cement could be purchased, but all other supplies would be taken from the nearby river. The orphanage did not have a concrete mixer; therefore, all mixing would have to be done by hand. However, getting additional labor was not a problem and it was estimated that a maximum of 10 yards of concrete could be poured in one day. The students requested cylinder samples from the site to determine the strength of the hand mixed concrete.

There was not any technical information available on the site conditions. The cross was to be built at the top of a hill. There was between 3 and 6 inches of topsoil above a layer of red clay-like soil and shale. Excavation equipment consisted of pick axes and shovels, but again due to the low cost of labor, excavation of the foundation would not be a problem. One concrete vibrator, miscellaneous hand tools, and power saws and drills were also available. Luckily, the site had recently been provided with access to electricity to aid in the use of the power tools.

Based on the aforementioned criteria and correspondence with the site foreman, the students determined that sheet metal formwork and wood scaffolding should be used for construction. Furthermore it was their opinion that if the foundation could be completed prior to their arrival it would be feasible to construct all elements of the formwork, scaffolding and cross during the five days of work. This assumption was then used to develop their design schedule, as the foundation design would need to be completed at least one week prior to the trip. The construction and design schedules are presented in Figure 1.

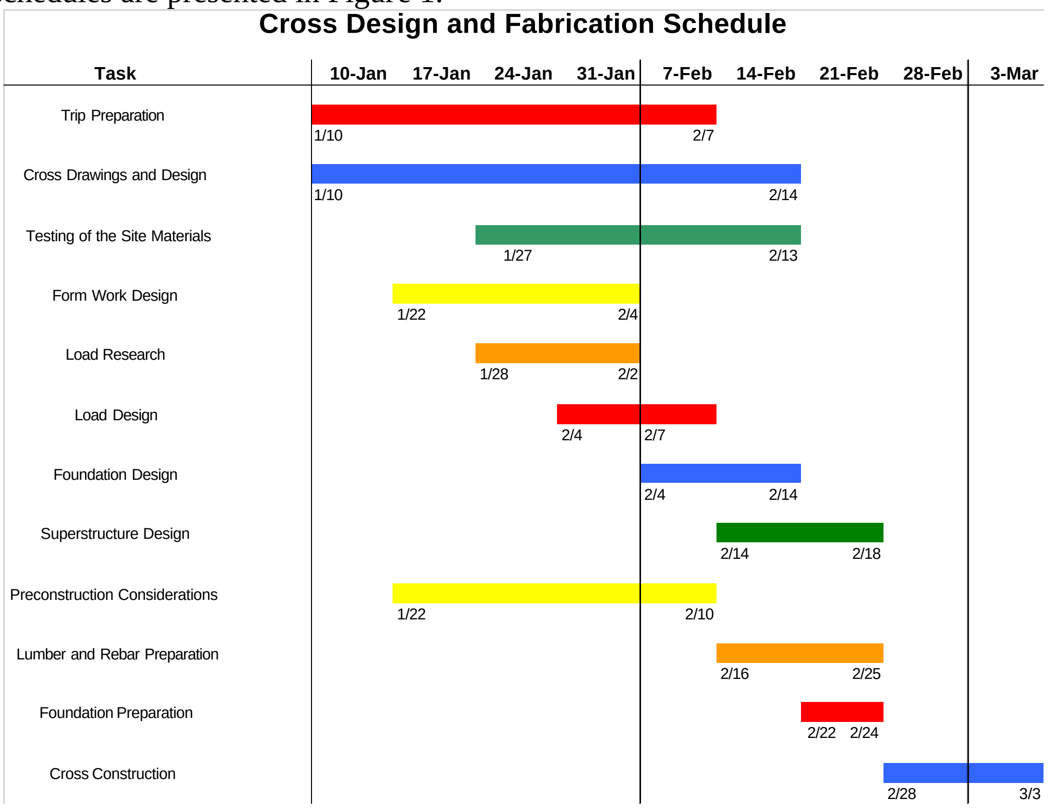

Figure 1: Construction and design schedule

The students quickly determined that besides its self weight, the cross would be subjected to no other gravity loads. Photos of the area demonstrated that most structures were non-engineered and research by the students found no governing structural code for Honduras. Consequently, it was decided that the design would be in accordance with the 1999 BOCA National Building Code. People from the site had noted that they periodically experience small tremors, and high winds. Research showed that the cross site was in a very active seismic area. Furthermore, Honduras is frequently hit by severe hurricanes, the most recent being in 1998 when Hurricane Mitch brought mass destruction and death. Further research of the seismicity and wind history was conducted, and ground accelerations and wind speeds were determined and used in conjunction with BOCA to develop the lateral loads for design.

As shown in Figure 1 the material testing program was conducted simultaneously with the load development and formwork design. Student inquiries as to the concrete mix design demonstrated that the process was far from scientific. Concrete was mixed by hand using a Portland-type cement, water, and aggregate taken from the local river. Construction photos from other work at the site showed that the slump could vary greatly; consequently, cylinder samples were requested. Due to time and sample transport constraints, only three concrete cylinders were shipped. Standard cylinder compression tests were conducted on the specimens, although the ASTM standard was not followed in preparing the cylinders. The average strength of the cylinders was approximately 1,800 psi based on two 14 day breaks and one 28 day test. In addition to the much lower strength, the failures showed many differences when compared to US concrete. The cylinder failures were not catastrophic and the failure surfaces appeared to be moist. Furthermore, there appeared to be a very low percentage of coarse aggregate in the Honduran samples.

The cross column and beam were then designed using 1800 psi as the design strength. Based on the load combinations and a conservative assumed value for the bearing pressure of the soil, a square footing was designed that utilized the available sizes of reinforcement. The foundation design was completed one week prior to the trip to ensure that the foundation would be finished prior to start of cross construction.

Design and layout of the formwork and scaffolding proved to be more complex than similar tasks in the United States due to the following third world imposed constraints:

1. Structural sheathing is extremely expensive and hard to obtain.
2. All structural lumber is cut by chain saw from trees on site.
3. Sheet metal and angle are available for formwork; however, due to limited finances the formwork would be needed to be recycled for other uses (work benches, shelves, walls, etc.).
4. There are no lifting devices on site; therefore,
   - all of the formwork would be assembled by hand;
   - all concrete would be poured by hand.

With guidance on these constraints from the Honduran foreman on site, the students designed a formwork scheme utilizing the sheet metal reinforced with steel angle stiffeners that would allow for three different levels of formwork that could be bolted into place. The designed allowed for the formwork to be recycled as workbenches for the workshop at the orphanage. Students also designed the scaffolding that would allow for the use of wheelbarrows, as opposed to individual buckets, in pouring the first 8 ft of the cross column.

Construction

The major tasks completed on each day of cross construction are outlined below. Figures 2 through 8 show the construction progress during the week. The foundation had been poured four days prior to the first day of cross construction. Furthermore, wood for the scaffolding had been cut, some of the concrete materials were on site, the first level (0-8 ft) of formwork had been fabricated, and electricity and water were made available on site prior to the start of cross construction.

Day One: A short safety meeting was held to discuss some hazards of the site typical of US jobsites, and some that were unique to a third world country, such as, tarantulas, scorpions, and poisonous snakes. The group was subdivided into teams that rotated between hauling concrete materials up the hill to the site, column rebar preparation (cleaning, cutting, bending), fabricating the formwork for the second level (8-16 ft), and construction of the first level of scaffolding. Figure 2 (left) shows the status of the scaffolding at the end of day one.

Day Two: Work commenced with placement of the first column vertical rebar and ties (Figure 2 - right). There was more hauling of materials up the hill, including the completed formwork for the first level (Figure 3), rebar, and more cement and aggregate. As rebar work commenced, a team started work on the beam formwork. By the end of the day placement of first level of formwork and the column ties to 8 ft were complete

Day Three: The rebar for the cross beam was cleaned, cut, and bent. Column ties were secured to the column from 8 – 16 ft, while the second level of scaffolding and the second level of formwork placement were completed. Figure 4 shows the ramp added to the scaffolding to allow for easier access to the first level platform. Work on the formwork for the beam and the top section of the cross continued.

Day Four: There were still more trips of cement and five-gallon buckets of aggregate to the top of the hill. The rebar and stirrups for the beam were installed (Figure 5) and the formwork placed. One team finished fabricating the final formwork for top portion of the column. The final progress is shown in Figure 6 (left).

Day Five: The final concrete materials were transported to the site. The final column ties were installed, the remaining formwork was placed, and a plastic hose was installed from the base to the top of the column to allow for running electric wire for the placement of lights on top of the cross.

Work for the concrete pour started with two crews of five hand mixing batches of concrete. Figure 6 (right) shows one of the crews mixing concrete. Concrete was placed in five gallon buckets and an assembly line of workers passed the buckets to the cross. The back panel (panel immediately in front of the scaffolding ramp) was left off and concrete for the first level of the column was poured through the opening. Concrete was vibrated in one foot intervals until the first level of formwork was full. The back panel of the second level of formwork was then bolted into place, and the pour commence. Ten cylinders were taken throughout the pour; four each from the first and second levels of the column, and two from the beam. The total pour took approximately four hours. Figure 7 shows the final moments of the pour and the assembly line of concrete buckets. All exposed surfaces were finished and covered with wet cardboard. The cross with formwork removed and the painted final product are shown in Figure 8, top and bottom respectively.

 

Figure 2: Scaffolding status at the end of day one (left); column rebar placement (right).

Figure 3: One of many hikes up the 100+ foot hill.

Figure 4: The second level of scaffolding is completed with a ramp to the first level.

Figure 5: A "little helper" expedites the rebar placement of the cross-beam.

Figure 6: End of day four (left) and mixing of concrete (right).

Figure 7: Placement of concrete in 5 gallon bucket increments.

Figure 8: The cross after the formwork was stripped (top) and the final product (bottom).

Outcomes

The students on the trip reported back to the students that were unable to attend about the week of work. The ten concrete cylinders were tested to verify that 1800 psi was a conservative design strength. Students were required to formally document the major differences between US and Honduran design and construction, and the design changes that occurred due to construction limitations. The major differences they noted included:

- Information gathering (lateral load information such as ground accelerations and wind velocities had to be determined based on research)
- Material availability (rebar, aggregate, structural sheathing and lumber)
- Material quality (1800 psi vs. 4000 psi concrete)
- Concrete preparation and placement methods
- Reinforcing steel preparation and availability
- Equipment for excavation, surveying, and transport and lifting of materials
- Communication (long response time from the site and Spanish to English translation problems while at the site)
- Recycling of formwork for other functions

Perhaps the most significant difference between work in the US and Honduras was the quality of the concrete. After the initial tests were conducted, the students believed that they could drastically improve the quality of the material by adding more coarse aggregate. They realized soon into the pour that adding significantly more coarse aggregate was not a feasible option due to the need to hand mix concrete. The students did convince local workers to add less water to their mixes, but the test results showed that the concrete strength was still quite low.

Foreseen events during the construction process that consumed far more time than envisioned included:

- Material procurement (Taking the ox-cart to the river to retrieve aggregate)
- Intermittent loss of power
- Plumbing of the formwork
- Material hauling up the hill to the cross site

These events lead to some shifting of the construction schedule and required some long workdays, but they did not impact the final outcome.

Overall, these students participated in a start to finish design and construction experience, and were required to reflect on and critique their work. They brought their designs to life while dealing with significant construction constraints. Furthermore, they successfully conquered the challenge set forth in the course, as they met a demanding schedule to build a powerful symbol for a community in great need of hope.

Continued Work

Due to aforementioned outcomes and the incredible experiences of all involved in this project the authors have incorporated this type of real world service project into the structural engineering curriculum on a permanent basis. Last year, spring 2001, students designed a split level reinforced concrete building to serve as a guest house/chapel. Over spring break the authors brought nine students to Honduras to break ground and construct seven of the foundations. This past semester, spring 2002, a group of ten students returned with the authors to the site to work on the elevated concrete slab in the building. The plans for next year are to return to finish the roof of the building. It is hoped that the cross project and the continued work will serve as examples of how to bring constructability issues to life for the students. The authors strongly encourage other universities to seek out relationships with local organizations in need of civil engineering services to aid in this process.

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