Design Engineer Construct : Building Large Scale Structures

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ABSTRACT: Building and design technology is drifting towards digital fabrication, digitally generated forms, and digital modeling. A capstone course at the university emphasizes the next step, constructing the forms generated in a structures technology course using concrete as a building material. Students develop a building in which the structural form reinforces the building system. Throughout the term, using hands-on activities, students learn about structural systems, building cost, construction sequencing, and fabrication. The capstone experience culminates with student teams, consisting of architects and construction management majors, creating a 1”=1’-0” concrete model.

1 THE GOAL

The ability to think in “3D”, the ability to visualize how a building is constructed, the ability to qualitatively understand building behavior are skills necessary to practice in today’s building industry. At our campus, architecture and construction management students participate in a series of hands-on exercises developed to link design, structures, and construction. Two separate courses have been developed which require students to design a space incorporating a building material. In both of the courses, the buildings are designed, engineered, and constructed by architecture and construction management students. In the capstone course described with this paper, the buildings are constructed with concrete and utilize wire mesh for reinforcement. The concrete models are built at 1” = 1’-0” and the students build the models using building techniques similar to those for a full scale building. Working collaboratively in groups of four, the students:

• Bend “rebar” (wire mesh) and place the bar for columns, beams, slabs, and shear walls
• Incorporate design principles for lap splices, hooks, and development length
• Fabricate formwork and create false work
• Explore the effects of formwork on concrete finishes
• Finish the concrete – screed, rough trowel, and hard trowel, etc.
• Develop schemes for solar and water features
• Learn first-hand about team work, collaboration, and construction sequencing.

The course provides a physical means for linking design, engineering (simple calculations, digital model, and detailing), and construction methods that cannot be conveyed in a traditional course setting. Additionally, the tactile nature of model building provides an active learning environment and helps students integrate the learning objectives from the technology sequence into future design work.
2 AN OVERVIEW: THE TECH SEQUENCE

The structural technology courses are based on buildings as systems versus buildings as elements. This is a major diversion from traditional engineering or technology based courses at the university. All of the technology courses are taught by engineering faculty, so the concept of building systems versus building components is a diversion from traditional teaching. (It’s common for engineering courses to emphasize component design, such as a beam, column, or wall) The overall objective of the technology series is to give architecture and construction management majors a sense of the whole building versus how to design a piece of building. Students discover how elements fit together to form a space and complete nominal calculations to establish the building mass. The last goal of the sequence is to empower the student. After completing the program, one should feel comfortable at a project meeting; understand the terms used at a job site, understand the design issues related to structure, and have the confidence to contribute to the discussion.

The structural technology series consist of three courses: building systems, small scale structures, and large scale structures. The sequence begins with an overview of stability using various systems; braced frames, moment frames, and shear walls. Students also learn about materials of construction and the impact of choosing timber versus steel versus concrete as a structural system. And lastly, the students are introduced to various floor framing options and how diaphragm configurations impact the placement of walls and frames which in turn impact space and egress.

The second and third courses address the application of building materials and systems based on the size (scale) of a building. In the second course, systems and construction concerns related to smaller scale buildings is covered. Typically, timber and steel options are explored, as well as, various forms of post and beam construction, and truss options.

3 ARCH 316: LARGE SCALE STRUCTURES

The third and final technology course is the emphasis of the paper. In this course large scale buildings are discussed. Topics related to high rise, long span, and tensile structure construction are discussed. Students gain a conceptual understanding of tall buildings and how to restrain these types of structures against wind and seismic using systems such as outriggers, bundled tubes, and mass dampers. And learn about shape finding and anchorage when dealing with tensile and fabric structures (See Figure 2.)

The culminating concept for the large scale building course is a module on concrete construction.

Figure 1: Model exploring stability and load flow using truss systems which create space and form
In the final exercise, students work collaboratively in groups of four. The typical group is two architects and two construction management majors. The student groups are responsible for scheming a building, establishing the load path for gravity and lateral load systems, estimating beam and column sizes, and lastly, incorporating a solar feature and a water feature into the project while developing a coherent architectural design.

The project kicks-off with a primer on concrete construction. Terminology, cost and labor, plus construction sequencing issues related to concrete construction are addressed. Students are exposed to rules of thumb for estimating concrete sizes as well, using both charts and shortened equations based on rudimentary load take-offs.

3.1 The Objectives of the Model

The purpose of the model is to reinforce the concept of structure and space, but also to infuse the process by which concrete structures are constructed. As noted previously, students learn hands-on how concrete is formed, what is building tolerance, scheduling, formwork design, and cost estimating, plus a myriad of other issues that require coordination when constructing a building. And since the students design and construct a building they essentially act as design-build teams.

3.2 Design and Pre-Construction

The calculation portion of the project is nominal, the students are required to use basic concepts such as tributary area, but otherwise the main objective is to identify a load path for the building. The premise being that a good designer can identify and scheme a load path and thus have the ability to converse with an engineer and offer suggestions.

The concrete projects are designed to require coordination and team work within each team and across teams as well. Building sites share a common boundary and are placed adjacent to each other as shown in Figure 4. Each site is required to have a channel traverse the site. The channel is continuous and each group must determine where the channel enters the site and where the channel exits the site. At each “property” line, the student teams must coordinate their work to create a continuous channel such that water can flow from one end of the building site to the other.

Formwork construction and finish is stressed throughout the design and construction process. Students quickly learn how embeds can be used to create shadow lines, how formwork impacts the exposed surfaces, and how to create a smooth concrete surface. As a primer to the construction process, students create a concrete platter. The concrete platter is approximately twelve inches square and two inches thick. Students build the formwork using various materials, include embedded items, and tape edges to better understand the relationship between formwork materials and concrete finish.
3.3 Breaking Ground

Students break ground by first demolishing the work created by the class before and then wetting, leveling, and compacting the soil. The benefits of compacting the soil, in this case settlement control, is discussed and the students observe the benefits of compacting moist soil by stepping on the soil and qualitatively measuring the soil depression. When the soil does not depress when the load of a “human compactor” does not appreciably deform the dirt, the soil is considered compact. A secondary advantage to compacting the soil is the dirt will hold firm when the students begin forming the foundation with earth forms.

Figure 3: The site after compacting and leveling, the string sets the centerline for the common channel

4 THE BUILDING PROCESS

The design-build teams replicate the building process for a concrete structure.

- Dig the foundation
- Place the foundation reinforcement and column and wall starter dowels
- File for reinforcement inspection
- Pour the foundation after inspection
- Fabricate and erect the column and wall reinforcement
- Erect the wall and column formwork including whalers and stiffeners
- File for reinforcement inspection
- Pour the columns and walls (the first vertical pour)
- Create the scaffolding and falsework to form the beams and slab at the next level
- Fabricate and install beam and slab reinforcement
- File for reinforcement inspection
- Pour the slab and beams (the first horizontal pour)
- Screed, level, and trowel the slab
- Repeat the vertical and horizontal pours to complete the building

4.1 Notable Learning Objectives; Stage by Stage

The building teams learn something different at each stage of the construction process. Each pour has notable concerns dealing with formwork, finishing, or continuity.

The main objective for horizontal pours is developing a level, smooth, and continuous floor. Students learn about reinforcement layering where primary and secondary framing members intersect or where slabs cantilever. Students are cognizant that reinforcement is placed on the tension side of a member, so for a cantilever slab the reinforcement must be placed on the top side of the floor. On more than one occasion, students have placed reinforcement on the bottom side of the slab and discover the slab cracks and fails when the scaffolding and formwork is removed. Also, the groups discover the benefits of using beams that are the same depth, but not necessarily the same width. They learn that it is easier and quicker (less labor) to erect scaffold-
ing for beams that are designed to be the same depth. And lastly, after the groups grapple with screeding the slab level, they discover that concrete must cure for a little while before hard trowelling the surface to obtain a smooth finish. The levelness of the floor and roof is related to the undercut for doors, or the slope on a roof, or ponding on an outdoor deck. All design issues that can be lectured in class, but emphasized using their completed models.

The vertical pours demonstrate the need for vertical control (plumbness) and the quality of the formwork construction. The story heights for most of the buildings are 15 feet or 15 inches in the model. Even at this small measurement the concrete builds up significant hydrostatic pressure. The students learn that walls cannot be formed with vertical pieces of masonite board alone, but require form ties or whalers along the height of the wall to prevent the wall from blowing outwards when the concrete is placed. An analogy to a milk carton is used where by the faces on the carton bow out due to the lateral pressure of the milk on the carton face. The other objective is consolidation. All the teams are reminded to vibrate and consolidate the concrete as they pour it into the walls and columns to avoid rock pockets and uneven consolidation. If the students do not rod the concrete and vibrate the forms adequately, they learn what a rock pocket looks like when the forms are stripped from the member.

And probably the greatest challenge when working with concrete is the time necessary between pours. In class, the cost and time comparison is to steel for a given building. Students understand that once steel arrives at a job site the construction process is continuous. But for a concrete structure, teams learn that time is required between each pour because the concrete needs to cure sufficiently before stripping the forms or removing the scaffolding. The students typically wait twenty-four hours between pours, so it’s critical that they develop a construction sequence that works with their schedules or finish date. Unlike a typical homework assignment, students cannot merely work straight through to complete the project, they must account for the incremental steps required in the construction process.

5 THE FINISHED PRODUCT

The projects are typically finished after six weeks of work. The design program requires that a solar feature and a water feature be incorporated into the design to provide a sense of excitement on presentation day. The students are given a time at which the solar feature should highlight or create a point of interest in the structure. To help them understand the possibilities, the top floor in the Phoenix Library is used as an example of light creating a dynamic effect and a feature on the summer solstice.

The water features typically employ water brushing across an articulated wall or column, a separate pool off the main channel, or a chute of water spraying a surface. But the water features also help articulate the common channel discussed earlier. The purpose of the common channel is to create coordination across teams. As seen in figure 6, the channel is a common feature that ties the site together as a whole and if one team doesn’t coordinate with the other the channel will not flow.

The use of water also provokes discussions about corrosion, crack control, and texture. Impromptu lectures related to requirements when building in wet environments, such as bridge piers in water, or lectures about the relationship of reinforcement spacing to crack width, or discussions about the dynamic effects of light, water, and shadow on textured surfaces are a result of including a water feature in the model.
6 CONCRETE MODELS: ASSESSMENT

The use of models as a teaching tool is well understood, models are used in studio courses to great success. In technology courses, the use of scaled models and in particular, those models that emulate real word practice, are invaluable. In the case of the concrete model, students learn the following:

• Concrete needs time to cure and scheduling pours or castings is critical.
• Providing lap splices for continuity and placing reinforcement on the tension side of beams and slabs is critical for stability of the structure- models have failed when the forms have been stripped
• Concrete construction is sequenced in prescribed stages because of material and mechanical limitations. It is impractical and extremely difficult to pour concrete over two stories
• Embeds need to be fabricated and placed to allow for removal
• Concrete finishes are a function of material porosity, such as glass which is not porous creates a smooth finish versus plywood which is porous and creates a comparatively rough finish

The ability to assess the learning objectives associated with models maybe harder to quantify. But exit quizzes show that over 90 percent of the students understand the relationship between formwork material and concrete finish, why concrete is consolidated, the location of pour joints and the impact on architecturally exposed concrete, and why reinforcement is used in concrete.

7 CLOSING THOUGHTS

Student and advisory council reviews have been very positive. While the concrete model is labor intensive, the students overwhelmingly agree it enabled them to learn more about construction and engineering than merely developing a set of calculations and structural drawings.

The models also allowed a level of creativity which is important for design students. The creation of space is an important aspect of design and the students are intrigued by the forms each team creates. But the most excitement comes from the unveiling of the water and solar features, simply because they occur at a specific point in time. Without these features the models would not have a vibrancy that water and light bring to a building.
8 PHOTOGRAPHS AND FIGURES

Figure 1: Photo by author
Figure 2: Photo by author
Figure 3: Photo by author
Figure 4: Photo by author
Figure 5: Photo by author
Figure 6: Photo by author

Figure 5: A finished model showing the water feature
Figure 6: The common channel
Figure 7: A simple solar feature below