Civil Engineering Capstone Design Courses Devoted to Structural and Architectural Renovation Projects

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Abstract: Engaging in a realistic design experience is widely seen as a fruitful way for engineering students to cap their undergraduate training. In industrial design, senior student projects often culminate in the fabrication of a functional prototype that can be evaluated by jury and tested by users. In civil engineering, however, real projects typically develop over time periods much longer than a single senior year, at scales too large to allow rapid prototyping. At the Department of Civil Engineering of National Taiwan University, our capstone courses of the last two years have sought to address this conundrum by various means. These include: focusing on building renovation projects of modest scale; working on campus projects for which there is a possibility of actual construction; using scale models and partial prototypes; involving professional architects and engineers, and starting capstone projects in the junior year to allow more time for students to pursue and materialize their designs. We describe one renovation project for which it was possible to complete the full cycle, from design to construction, over a span of two years coinciding with the junior and senior years of the student designers. The second project, likely to remain a simulation exercise, nevertheless incorporated various means to make the design process more realistic. For both actual and simulated projects, addressing the renovation of an existing structure in dialogue with users and owners help students ground their capstone design experience in reality.

Keywords: Capstone Design, Design to Construction, Structural and Architectural Renovation.

Introduction

Around the world, a number of civil engineering programs are seeking ways to integrate realistic design experiences in the undergraduate curriculum. These include programs at Stanford University (Fruchter, 2001), George Mason University (Arciszewski, 2009), the Technical University of Denmark (Jensen and Almegaard, 2011), and the Massachusetts Institute of Technology (Einstein, 2013). At the Department of Civil Engineering of National Taiwan University, we started experimenting in 2010 with a sequence of cornerstone, keystone, and capstone design projects, targeted respectively at freshman, sophomore, and junior/senior undergraduates (Capart et al., 2013). For these projects, one of our objectives has been to let students test their ideas in practice by combining digital design with material fabrication or construction.

For the mandatory cornerstone course, first year students use jet-cut aluminum to build and test scale models of their structural designs. The optional keystone course allows second year students to design and build 5 m span wood bridges, in cooperation with architecture students from Shih-Chien University (Hsu and students, 2013), and to design and fabricate functional pneumatic toys (Capart et al., 2013). For the capstone course, however, we have found it more difficult to complement design with a meaningful material component. Our first attempts (Wu et al., 2011) sought to ground projects in reality by targeting real sites: Xitou Forest, for the design of a cableway system, and Wushe Reservoir, for the design of sedimentation countermeasures. The design process included user and field surveys, and some lab experimentation, but the final result of students’ work was limited to written and oral reports, without a material product. Scaled physical models were produced in later editions, but did not greatly improve on the scale models that students can already produce in their first and second years.

In 2012, an opportunity arose for students to pursue a real project, when the department considered renovating a student space in our own building. The large first floor space, previously devoted to laboratories, had become a space for student activities, but had not been transformed in any way to meet the new user requirements. A planning stage in which students participated produced attractive proposals (Mu and students, 2012), and we decided to devote a capstone course to the design of a feasible structural and architectural renovation. Although the course was open to both junior and senior students, only juniors enrolled (save for one senior), and this allowed student designers to get involved in the project over more than one year. In this contribution, we describe the resulting capstone experience, which culminated in actual construction.
We also describe a new edition of this capstone course, currently in progress with a new generation of juniors and seniors. It again involves the renovation of an aging campus building, but is likely to remain a simulation exercise. Nevertheless, a number of lessons learned from our experience with a complete design-to-construction project have allowed us to improve the realism of this new edition. Below, we first describe the contents and approaches of the capstone courses. We then evaluate the courses in light of the four capstone aims proposed by Gardner, Van der Veer and Associates (1997) and adopted as guidelines by National Taiwan University (Center for Teaching and Learning Development, 2012). These four aims are integration, closure, reflection, and transition.

**Student Space Renovation Project**

**Student Assessment of Structural Retrofit Schemes**

The student space renovation project involved two components: first, a retrofit of the existing reinforced concrete (RC) structure, to allow some alterations to the building yet increase safety against earthquakes; secondly, the design of new elements, in particular a new mezzanine floor to allow more diverse uses of the large space. For both components, structural and architectural considerations were to be jointly taken into account.

To explore different ways of shoring up the structure, student teams first investigated various retrofit schemes (figure 1). For each scheme, students fabricated a 1:14 scale model of a single building frame strengthened by their proposed retrofit. Analogue materials were used (soldered copper substituted for reinforcement steel, and a sand-gypsum mix substituted for concrete), to facilitate fabrication at small scales yet produce scaled behaviors similar to real RC frames (Harris and Sabnis 1999; Lu et al., 2007; Knappett et al., 2011).

Students then subjected the model frames to quasi-static pushover tests. In these tests, vertical loads are kept constant, but lateral loads are gradually increased until failure to model the effects of horizontal ground motions. These experiments allowed students to acquire a better feel for the way reinforced concrete structures behave under earthquake loads, and to compare the performance of their different retrofit approaches compared to a reference bare frame (no retrofit) constructed using the same model materials.

Based on those tests, supplemented by advice from experienced structural engineers, a scheme involving wing walls and a new grade beam was selected. To investigate whether this scheme could more than compensate for the removal of a wall infill, students learned to simulate frame behavior using hand calculations and professional structural analysis software (ETABS). To check actual conditions below grade, an exploration pit was dug at this stage. Students then performed a new round of scale model tests using the verified dimensions and calculated wing wall sections. The experiments and calculations confirmed the suitability of the proposed scheme, which the students defended in the final design review of the semester. The conclusions of the student assessment were not altered by the subsequent professional analysis, performed by the practicing engineer in charge of the final renovation design.

**New Architectural and Structural Components**

For the second component of the course, students developed designs for new architectural and structural components, including a mezzanine floor and its staircase. This took place in parallel with the development of structural retrofit schemes over the Fall 2012 semester. At the end of the semester, however, proposals were not nearly as mature as the structural retrofit schemes. We therefore extended the effort beyond the Fall semester. A group internship at a professional wood workshop took place during the Winter. This allowed student designers to work with craftsmen to developed prototypes of possible components of the mezzanine and staircase. The ability of students to produce feasible designs that could actually be constructed progressed greatly as a result (for a detailed description, see Chung et al., 2013).

In the Spring 2013 semester, the students who participated in the Winter workshop then continued to develop their designs, in dialogue with professional architect and structural engineer, and with the future student users of the renovated space. Five teams of students were responsible for different components of the design, and also met regularly to seek consensus on how to assemble the parts together into a coherent proposal. This culminated in the drafting by students of detailed construction drawings, including both wood and steel components, carefully integrated together (figure 2).

By the end of the Spring semester, student designs had progressed markedly, and convinced the department to go ahead with implementing the scheme. Architect and structural engineers were commissioned to professionalize the designs, including structural safety calculations and the preparation of bidding documents. Upon securing funding, the work was subdivided into three parts, assigned respectively to a general contractor, a specialty steel contractor, and the wood workshop which hosted the Winter internship (which forms part of the Experimental Forest of National Taiwan University).
Figure 1. Assessment of existing structure and retrofit options for the student space project. Top to bottom and left to right: students survey the existing structure, composed of parallel RC frames; fabricate scaled RC beams composed of soldered copper and a gypsum mix poured into wood formwork; conduct pushover tests on a scaled model of a single frame, strengthened by wing walls and a new grade beam; discuss experimental model response with an experienced teacher; simulate frame behavior using professional software, guided by practitioners; report the results of their retrofit assessment. After further professional involvement, the option investigated by students was adopted for actual implementation.
Figure 2. Design of new structural and architectural components for the student space project. Top to bottom and left to right: concept sketch developed by students prior to the course; preliminary student designs for a mezzanine structure and staircase; design review by a professional architect; fabrication of a flitch beam prototype during a winter internship at a professional wood working facility (for a detailed description of this workshop, see Chung et al., 2013); discussion of steel assembly details with a practicing structural engineer; student drafting of the construction drawings, taking professional input into account; 3D view of the final student design combining wood (brown) and steel (gray).
Actual Construction

Actual construction started in August 2013, and provided many opportunities for continued involvement by the student designers (figure 3). Two of the students interned as junior worksite engineers. They were tasked with documenting the progress made by the general contractor, and with following up on design changes, some due to new information which emerged during the construction process. As an example, one of the brick walls to be removed turned out to include an unexpected RC column, which was not removed for the sake of structural integrity.

Other students participated in incorporating design changes suggested by the structural engineer, steel and wood contractor. Although no essential feature of the student designs was altered by engineer and contractor, many small changes were made. This included details of the steel assembly, improvements to the interface between wood and steel components, and dimension adjustments to fit the actual geometry of the space after completion of the retrofit work by the general contractor. An interesting change to the staircase was the contractor’s recommendation to switch from an even to an odd number of steps, in line with construction practices deemed auspicious by traditional Taiwan builders.

Last but not least, student designers had the joy of seeing their designs gradually materialize over the semester. Milestones included the partial demolition and excavation, the pouring of concrete for the new grade beams and wing walls, the fabrication and erection of the steel structure, pull-out tests to verify the anchorage of the steel columns onto the RC footings, and the fitting of the wood elements of the mezzanine structure, deck and staircase. The renovated space was inaugurated on January 10, 2014. The happy occasion was attended by the student designers and many of the craftsmen, professionals and instructors who contributed to the project.

Old Library Renovation Project

Project Background

Building on our experience with the student space project, a new capstone course centered on renovation was offered in the Spring 2014 semester to a new generation of students. The project focuses on the hypothetical renovation of an aging campus building: the old library of the College of Management. This building was originally constructed by the US army when it operated an air station near National Taiwan University. It was later incorporated into the university campus and used as a college library. For many years, the aging building has hosted the student associations of the College of Management. The building has not been significantly adapted to suit this new function, its roof leaks, and the structure is only marginally safe. No renovation is currently being considered by the school because the building may be torn down to make way for a new development. Nevertheless, the building is attractive as an interesting case for a simulated renovation project.

Structural Assessment

Focused on this building, the new edition of the capstone project again included two components: a structural assessment of the existing structure, and the development of renovation proposals including new roof designs (figure 4). Two sections were opened to accommodate the increased number of students wishing to enroll in the course. For the structural component, student teams initially conducted a survey of the existing building. As the building is more complex than the student space, different groups were tasked with assessing different frames of the building, taken respectively in the longitudinal and transverse directions.

Improving upon the more ad hoc training provided previously, tutorials were organized to teach students how to assess the structural safety of RC buildings. Students learned to calculate loading cases and pushover curves using hand calculations, as well as using professional structural analysis software (ETABS). The earlier student space project was used as a great source of examples for presentation and practice, before students applied what they learned to the old library case. To help students get a feel for the construction and behavior of RC structures, each team constructed a 1:12 scale model of the frame they were tasked with. Models were again constructed from soldered copper and gypsum mixes, and subjected to laboratory pushover tests. Based on their calculations and experimental results, students presented their assessment for technical review by instructors and practicing structural engineers.

New Architectural and Structural Components

In parallel with the structural assessment, student teams developed proposals for structural and architectural improvements to the existing building (figure 5). Teams subjected their evolving concept to peer review, then professional review by practicing architects. After making changes in light of these reviews, students prepared draft proposals for presentation to the current users and manager of the building (student association representatives and the Vice-dean of the College of Management). Although the proposals concerned a simulated renovation not currently considered for implementation, a lively discussion ensued, offering students a quite realistic experience of meetings between clients and designers (figure 6).
Figure 3. Implementation of the structural and architectural renovation scheme for the student space project. Top to bottom and left to right: design presentation to future users of the space; wall demolition; construction of the wing walls and new grade beams, including footings supports for the mezzanine structure; student monitoring of worksite progress; on-site erection of the mezzanine steel structure; anchor bolt pullout tests; fitting of the wood components of the flitch beams; student designers examine the nearly completed mezzanine deck. The steel contractor redrew the students’ steel construction drawings, but the wood contractor worked directly from the student drawings.
Figure 4. Assessment of existing structure for the old library building project. Top to bottom and left to right: students survey the existing structure, learn how to calculate the seismic capacity of typical RC structures, using the student space project as example; calculate the seismic capacity of the old library structure by hand, and using professional software; build structural scale models using soldered copper and a gypsum mix; conduct pushover tests of their model frames; report the results of their structural assessment using a CAD sheet summarizing their assumptions, calculations, and experimental results; discuss their assessment during a technical review session with a practicing structural engineer.
Figure 5. Development of renovation proposals for the old library project. Top: peer review of preliminary proposals for renovated roofs. Bottom: white board design of key structure details.

Figure 6. Student renovation proposals for the old library project. Top: draft student proposal poster. Bottom: presentation of draft student proposals to users and manager.

Evaluation

How much do such design projects contribute to the students’ capstone experience? Gardner, Van der Veer and Associates (1997) and the NTU Centre for Teaching and Learning Development (CTLD, 2012) recommend that important dimensions of the capstone experience should include integration, closure, reflection, and transition. The design projects described above address some, but not all of these dimensions.

Regarding integration, design projects focused on building renovation are an excellent way to achieve vertical integration of skills and knowledge acquired by students at various stages of their undergraduate education. These include operational skills acquired by students in their freshman year, such as surveying and engineering graphics, basic analytical abilities acquired in the sophomore year, in courses on structural mechanics, and their application to the most common structural elements and materials learned in the junior year, in courses on reinforced concrete. Likewise, a course on construction management has equipped students with knowledge of the organizational and budgetary context of civil engineering projects. The capstone design project further connects these skills and domain knowledge to design abilities developed during cornerstone and keystone design projects. The joint consideration of structural and architectural issues also encourages students to bridge between a core sub-discipline of civil engineering (structural engineering), and a discipline beyond the strict confines of civil engineering (architecture). The above design projects, however, do not address the horizontal integration between different civil engineering sub-disciplines (geotechnical, hydraulic, transportation engineering, etc.)

The capstone design projects contribute to closure by allowing students to demonstrate the mastery they have acquired with various skills and disciplines. Students have the opportunity to produce technical drawings, craft scale models, and develop design proposals that approach or attain professional quality. For the student designers who participated in the student space project, an exceptional degree of closure was achieved when students saw their designs actually constructed. Even when projects cannot be brought to such degree of completion, the products of the capstone courses supply a strong closing chapter to students’ design portfolio.

Reflection is a dimension not currently targeted by our capstone design projects. The capstone projects emphasize creation over reflection, and their primary aim is to encourage students to actively
practice design. Some reflection does occur when students evaluate their designs jointly with instructors and professionals, but this evaluation typically focuses on design products rather than design process. Neither do the capstone projects aim to let students reflect on their broader learning itinerary since their freshman year.

Transition is addressed in various ways by the capstone projects. The most important transition they seek to achieve is one between passive reception and active practice. Ill-defined problems must be identified and solved, using resources that students must actively corral from various sources. The projects also seek to bridge between individual learning and team work, with opportunities for students to develop their skills as leaders and contributors to team efforts. A transition toward professional attitudes is sought by challenging students with realistic problems and tasks, and allowing students to interact with the professionals who intervene as mentors and reviewers.

Complementing the capstone design projects, our department has developed other initiatives which contribute to a more comprehensive capstone experience. This includes a summer internship program, typically pursued by students between their junior and senior years. Internships are preceded by a semester-long seminar, which provide opportunities for students to reflect upon their strengths and interests, and meet with a variety of guest professionals to discuss the skills and attitudes needed to thrive in engineering practice.

The senior year is also an important transition between undergraduate and graduate study: students apply for graduate programs in the middle of their senior year. In the second semester, those who go on to graduate school in our own department often start to work on research projects with their future graduate advisors. Those who aim to transfer to other programs, on the other hand, typically enroll in elective courses related to their target field of graduate study. Finally, a number of seniors participate in international exchange programs. Because of these competing demands on students’ preoccupations during their senior year, our experience is that the junior year and first semester of the senior year are the time periods most suitable for intense student involvement in capstone design projects.

Conclusion

Capstone projects focused on structural and architectural renovations feature a number of advantages. Because projects target existing buildings, students must directly engage realistic construction issues. Design efforts, moreover, can be conducted in dialogue with users and managers of the building. The projects allow a strong vertical integration of skills and knowledge acquired by civil engineering students at various stages of their undergraduate education, from engineering graphics to reinforced concrete. They also involve architectural considerations beyond the strict confines of civil engineering. These advantages accrue regardless of whether renovation projects can actually be implemented or only be simulated. The perspective of actual implementation, of course, provides a strong motivation to develop proposals further, and new opportunities for learning occur during the construction stage.

To provide opportunities for greater degrees of completion, possibly up to actual construction in exceptional cases like the student space project, and to avoid conflict with the many competing demands faced by senior year students, we recommend starting capstone projects in the junior year. Also, cornerstone and keystone projects pursued in the freshman and sophomore years constitute an important preparation for successful capstone projects. The student designers who completed the student space project were the first generation of students who experienced the full sequence of cornerstone, keystone, and capstone projects. This allowed them to take their design efforts much farther than earlier students for whom the capstone course was the first design experience.

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