121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #9050

Structural Engineering for Architecture and Construction Management Students – A New Approach

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Introduction

Architecture and construction management students can often graduate with a weak foundation in structural engineering leaving them less than fully prepared to take on their future roles in industry. The California Polytechnic State University, San Luis Obispo is well positioned to fill this potential gap. The Architectural Engineering (ARCE) Department at California Polytechnic State University, San Luis Obispo is fortunate to be one of five departments located within the College of Architectural and Environmental Design (CAED), a college that also includes the Architecture (ARCH) and the Construction Management (CM) departments. A great benefit of this arrangement is that considerable interaction takes place amongst the departments mirroring the interaction and collaboration that occurs in industry. One of the more successful interdepartmental collaborations has been amongst the architectural, construction management and architectural engineering departments. This exchange of information and students encourages greater knowledge and understanding of each other's disciplines and prepares students for a practice that increasingly values such interdisciplinary collaboration.

Until this year, the ARCE department offered a sequence of five support courses that was taken by both architecture and construction management students and gave them a solid grounding in statics, properties of materials and structural systems. The final two courses in this sequence were titled *Small Scale Structures (ARCE 315)* and *Large Scale Structures (ARCE 316)*. These two courses were unusual in that they were designed not for ARCE students but solely for the ARCH and CM students.

The five course sequence has been recently reconfigured in response to requests by the ARCH and CM Departments whose students they serve. The reconfiguration is in response to two specific requests. A new ARCE 315 includes content for both small and large scale structures with timber, structural steel and reinforced concrete structural systems and is now being taken by both ARCH and CM students. A new ARCE 316 that will be integrated into the third year architecture studios and taken by ARCH students only is being created.

The focus of this paper is the new ARCE 315 course. The overall goal of the course remains to give the ARCH and CM students' structural engineering skills so that in their careers as project leaders they will better understand structural engineering systems and principles. The new ARCE 315 has been developed over the last year in consultation with the ARCH and CM departments. The challenge has been to select the appropriate mix of content from the two original courses to include in the new ARCE 315. This course was taught for the first time in Fall Quarter 2013; its organization and content are being adjusted based on lessons learned.

This work in progress paper will present the background of the original five course sequence and the recent changes, the learning outcomes and content developed for the new ARCE 315, the two student projects through which the course contents were applied, and the lessons learned in Fall quarter 2013 and proposed modifications.

Background of the Five ARCE Course Sequence

The curriculums for the ARCH and CM students at California Polytechnic State University, San Luis Obispo have, for many years, included structural engineering courses taught by the ARCE department. In 2005 the ARCE department updated the sequence of courses required for the ARCH and CM students. The earlier six course sequence, which included three structural material specific design courses, was replaced by a five course sequence in which the three material design courses were replaced with two courses focused on small scale and large scale structures.

As restructured, the curriculum for ARCH and CM students included a total of five ARCE courses giving them a solid grounding in structural engineering principles, design and systems. The five one-quarter courses, with the number of units and hours each week, are listed below:

- *Structures I (ARCE 211): 3 units with 2 hours of lecture and two hours of activities per week*
- *Structures II ARCE 212): 3 units with 2 hours of lecture and two hours of activities per week*
- *Structural Systems (ARCE 226): 3 units with 3 hours of lecture per week*
- *Small Scale Structures (ARCE 315): 4 units with 4 hours of lecture per week*
- *Large Scale Structures (ARCE 316): 4 units with 4 hours of lecture per week*

The first two courses, *Structures I (ARCE 211)* and *Structures II (ARCE 212)*, are taken by ARCE as well as ARCH and CM students. These are rigorous courses that introduce statics and the mechanics of materials. These two classes combine traditional lectures with activity sessions in which students build physical models to enhance their understanding of the content. *Structures I* is an introduction to statics and the creation of simple three-dimensional structures. Skills to analyze structures composed of axial force members are developed. *Structures II* is an introduction to shear and moment diagrams using the principles of statics and the application of the diagrams to simple three-dimensional structures. Skills to analyze structures composed of bending (beams) members, particularly, are developed.

Following *Structures I* and *Structures II*, is a course entitled *Structural Systems (ARCE 226)*. This course is for ARCH and CM students only. This is the course in which the focus shifts from structural elements to building structural systems. Working with the knowledge students gained in *Structures I* and *Structures II*, students develop the skills to analyze simple buildings composed of axial and bending members. They learn about structural stability in 3D, gravity and lateral loads, the development of framing plans, the behavior and comparison of structural building systems, framing schemes and building configuration related to vertical and lateral loads.

Following the *Structural Systems* course, the ARCH and CM students took *Small Scale (ARCE 315) Structures* and then *Large Scale Structures (ARCE 316)*. While the *Structural Systems* course is material neutral, the *Small Scale Structures* and *Large Scale Structures* courses were material specific. The *Small Scale Structures* course focused on timber and single story steel framed buildings. The *Large Scale Structures* course focused on multi-story reinforced concrete and structural steel framed buildings. Students learned the characteristics, advantages and disadvantages of different structural systems, how to evaluate the different systems and how to develop the preliminary structural designs of buildings. The courses also incorporated aspects of foundations, cladding, and long span and high rise structures.

The primary goal of this five course series was to give these students tools that will assist them in their careers as project leaders so they can better produce efficient integrated designs and collaborate effectively with their structural engineering consultants and thus lead successful projects. The benefits of understanding structural principles apply to both ARCH and CM students. Architects typically take a lead role in building design and so an understanding of structural principles can enhance their ability to produce design concepts that are coordinated with an efficient, well thought out structural system. Understanding structural concepts and nomenclature allows the architect to more effectively communicate with their structural consultants and better develop the structural system. In addition, the architect, as team leader, often directly communicates with the client or owner and a better understanding of structural principles allows them to convey the implications of structural decisions to the owner. The decisions of an informed owner are more likely to result in a successful project. An understanding of structural engineering principles acquired as an architecture student can therefore be of great benefit in his or her career.

These courses are of similar benefit to CM students. Construction managers are increasingly involved during the design phases of projects. In projects that use a design-build process, they often also act as team leaders. For them, knowledge of structural principles also enhances their ability to collaborate with the structural consultants, better communicate with owners and help make effective structural decisions. Construction managers are often involved in developing construction costs; a clearer understanding of the implications of structural decisions can be of great value in this regard.

The five course sequence has been recently reconfigured in response to requests by the ARCH and CM Departments whose students they serve. The reconfiguration is in response to two specific requests. The CM department needed to eliminate one course from the five-course sequence required of their students in response to a directive to reduce overall program units. The ARCH department requested an explicit integration of structural content into their upper division third year design studios. The solution, which served both departments, was composed of two actions. One was to revise the content of ARCE 315 so that it included content for both small and large scale structures with timber, structural steel and reinforced concrete structural systems. This course, now titled *Structural Design for Non-Majors*, is being taken by both ARCH and CM students. The other action was to modify the structure and content of ARCE 316 to create a course integrated into the third year architecture studios. This course with the new title of *Structural Integration for Architects* will be taken by ARCH students only.

Figure 1 shows the earlier and current five ARCE course sequence.

EARLIER FIVE COURSE SEQUENCE	CURRNT FIVE COURSE SEQUENCE
Structures I (ARCE 211) ARCE – ARCH - CM	**Structures I (ARCE 211) ARCE – ARCH - CM**
Structures II (ARCE 212) ARCE – ARCH - CM	**Structures II (ARCE 212) ARCE – ARCH – CM**
Structural Systems (ARCE 226) ARCH - CM	**Structural Systems (ARCE 226) ARCH - CM**
Small Scale Structures (ARCE 315) ARCH - CM	**Structural Design for Non-Majors (ARCE 315) ARCH – CM**
Large Scale Structures (ARCE 316) ARCH - CM	**Structural Integration for Architects (ARCE 316) ARCH**

Figure 1: Five Course Sequence Summary

With the reconfiguration of the five course sequence both ARCE 315 and ARCE 316 needed to be redefined and new learning outcomes and course content developed. The learning outcomes and contents of ARCE 316 are now being developed. A description of the development of the new ARCE 315 follows.

Development of Learning Outcomes and Content for *Structural Design for Non-Majors (ARCE 315)*

There is little published literature on the subject of structural engineering for ARCH and CM students that might have provided guidance. The engineering education literature includes discussions of a number of interdisciplinary courses. Some of these interdisciplinary courses include engineering students from multiple discplines[1,2] or engineering students and business or marketing students[3,4] and some interdisciplinary courses are focused on the design and construction disciplines and include architecture and construction management students as well as engineering students[5,6,7]. However the literature on these courses is of limited relevance and provides limited guidance. Although the courses described in this paper have an interdisciplinary component, they are not really interdisciplinary. They teach structural engineering skills and principals to non-engineering (ARCH and CM) students but do not contain the content of multiple disciplines and do not function as interdisciplinary courses.

Saliklis, et al describe the different curriculum approaches typically employed for architectural and engineering programs[8]. They describes how engineering programs work from the "ground up" starting at a very detailed level and gradually advancing to systems only at the end of a program, while architectural programs typically use a studio approach which introduces students to the design of full projects at an early stage. Courses involving architecture students with engineering content might ideally recognize these two approaches.

The new learning outcomes and content were therefore developed using the experience with the earlier courses and goals developed for the new course. The most direct approach to the development of learning outcomes and content for the new ARCE 315 was to select the key material from the final two courses in the original ARCE sequence, *Small Scale Structures (ARCE 315)* and *Large Scale Structures (ARCE 316)*. The challenge, of course, was to determine what material to maintain and what to eliminate while still maintaining the overall goal of giving the architecture and construction management students the structural engineering knowledge they will need in their future careers as project leaders.

The learning outcomes for the earlier courses *Small Scale Structures (ARCE 315)* and *Large Scale Structures (ARCE 316)* have been repeated below for reference.

Small Scale Structures (ARCE 315) – Learning Outcomes

Upon completion of this course, students should have the following as applied to small scale flexible diaphragm structures in steel and timber:

1. Ability to trace gravity and lateral load paths.
2. Ability to develop preliminary gravity and lateral load resisting systems including preliminary sizes for beams, columns, walls and braces.
3. Ability to understand conceptual principals about connection design
4. Ability to describe common structural systems, including advantages and disadvantages relative to performance, cost and function.
5. Ability to describe the effect of configuration on building performance, cost and function.

Large Scale Structures (ARCE 316) – Learning Outcomes

Upon completion of this course, students should have the following as applied to medium and large scale rigid diaphragm structures in steel and concrete:

1. Ability to trace gravity and lateral load paths.
2. Ability to develop preliminary gravity and lateral load resisting systems including preliminary sizes for slabs, beams, columns, walls and braces.
3. Ability to understand conceptual principals about connection design.
4. Ability to describe the structural systems and special issues associated with high rise and long span structures.
5. Ability to describe common structural systems, including advantages and disadvantages relative to performance, cost and function.
6. Ability to describe the effect of configuration on building performance, cost and function.

Given the challenge of compressing this material into a single course, alternate approaches such as incorporating some material into the earlier three courses of the ARCE sequence were considered. The first two courses of the sequence, *Structure I and II (ARCE 211 and 212)*, are integrated into course sequences for ARCE as well as ARCH and CM students and reconfiguration to absorb new material would have been difficult at best. The third course in the five course sequence, *Structural Systems (ARCE 226)*, contains sufficient content, judged to be essential, so that it could not absorb new material. The decision was therefore made to select key elements of the learning outcomes and contents of *Small Scale Structures (ARCE 315)* and *Large Scale Structures (ARCE 316)* and use them as a basis for the new *Introduction to Structural Design (ARCE 315).*

Goals were developed to provide guidance in compressing the material from two courses into one. They were: 1) include content with an appropriate level of structural engineering rigor, 2) provide a balance of detailed engineering knowledge and big picture design considerations and 3) recognize that this is the culminating course for CM but not for ARCH students. The overall goal, of course, of preparing ARCH and CM students for the future careers remained.

The question of the appropriate level of structural engineering rigor received much discussion. The conclusion was that the calculational content needed to be reduced because of the reduced time available. Although the calculational content in the previous courses as believed to be important, configuration content was judged to be vital to the students' future roles and so it was maintained. This strong focus on configuration issues was believed to maintain an acceptable level of structural engineering rigor.

One example of a configuration issue is the preparation of framing plans. This ability was believed to be of significant importance and was covered for each of the three structural materials, timber, steel and concrete. Reasonable spans, spacings and locations of framing members were taught. This was judged to be more important that determination of exact sizes. Accordingly, member depths were estimated based on "rules of thumb" rather than calculation as had been done previously.

Seismic configuration issues such as the horizontal and vertical placement of bracing elements was also considered to be important and significant time was allocated to them. Guidelines and simplified calculations were developed and used in place of detailed seismic analysis. These configuration topics were practiced in class and in homework and project assignments.

The balance of detailed engineering knowledge and big picture design considerations was addressed in a couple of ways. The characteristics of the three structural materials, such as strength and stiffness, sustainability and their potential for decay, corrosion and fire damage were maintained because of their value in selecting materials for project use. Characteristics of structural systems were discussed for the same reason. These are generally big picture topics. Also included were discussions of details of engineering discussion where they related to a systems characteristics, performance or constructability.

Recognizing that ARCE 315 is now the culminating course for CM but not for ARCH students, the learning outcomes and contentof *Small Scale Structures (ARCE 315)* and *Large Scale Structures (ARCE 316)* were reviewed to determine what content need not be included in the new ARCE 315 but could be shifted to the new ARCE 316. For example, Architecture faculty, expressed a strong interest in tall building structural systems and long span structures. These were not considered core content by Construction Management faculty. Tall buildings and long span structures are structural types less likely to be encountered in practice by construction managers. Cladding was also judged to be more important by ARCH faculty than by CM faculty. This content will therefore be included in the new ARCE 316 where it will be effectively integrated into the third year architectural studios. The scope of foundations, shoring and underpinning was reduced because that material is to some extent covered by the CM program and can be supplemented in the new ARCE 316.

These discussions resulted in the following learning outcomes. These received approval of Architecture and Construction Management faculty representatives as well as of ARCE faculty.

Introduction to Structural Design (ARCE 315) – Learning Outcomes

Upon completion of this course, students should have the following abilities as applied to small and large scale structures in timber, steel and concrete:

1. Describe common structural systems, including advantages and disadvantages relative to performance, cost and function.
2. Describe the effect of configuration on building performance, cost and function.
3. Develop preliminary gravity and lateral load resisting system layouts including preliminary sizes for slabs, beams, columns, walls and braces.
4. Describe foundation systems.

With preparation and approval of these learning outcomes was the acknowledgement that the depth of some of the material covered was reduced and that some contents was lost or shifted to other courses. Still it was believed to represent a good balance of material and will provide the students with a strong background in structural engineering knowledge and skills.

Building Projects

Key to the course was the inclusion of student building design projects. These were team projects in which students prepared preliminary structural designs for the types of building they are likely to encounter in their careers. The products of these projects were structural framing plans and boards describing characteristics and the design process. The goal of the projects was to reinforce the lecture material and give students another opportunity to practice skills. They also provided expectations of the deliverables for conceptual structural submittals.

Two projects were included in the Fall 2013 course. The first was a small building structure. Students selected one of four buildings, a school, library, natatorium and gymnasium. Because of time constraints the scope of this project was limited to the roof framing.

This was a warm-up for the second project, a multi-story building of steel or concrete construction. Students choose from eight buildings: office, hotel, university classroom, university research laboratory, convention center, hospital, library and community center. The eight buildings were based on actual buildings and ranged in size from three to ten stories and 70,000 to 160,000 square feet. Students were given building programs and were required to develop building floor plans that were integrated with conceptual structural designs. There were two informal presentations with reviews by students as well as the instructor.

Beyond the structural material, this project included two other aspects intended to bring the design process closer to that of actual projects. One was a brief introduction to fire resistive construction requirements relative to building size and occupancy. Students were required to demonstrate that their selected structural system was compliant with the building code requirements for construction types. The other was the introduction of planning considerations. Students received a lecture from a professor in the City and Regional Planning Department relative to city planning requirements and were given planning documents for an actual city. They were required to select a site and demonstrate that their proposed project was appropriate for the site and met city planning requirements for size and type.

The products of these projects were floor plans, structural framing plans and sections and boards describing structural system characteristics and the design process. Calculations were minimal. Projects were evaluated relative to appropriateness of the structural system selection and configuration and presentation of their design and decision making process. The projects were judged to be a success with significant improvement shown between the first project and the second.

Examples of selected material from students' submittals are shown in Figure 2.

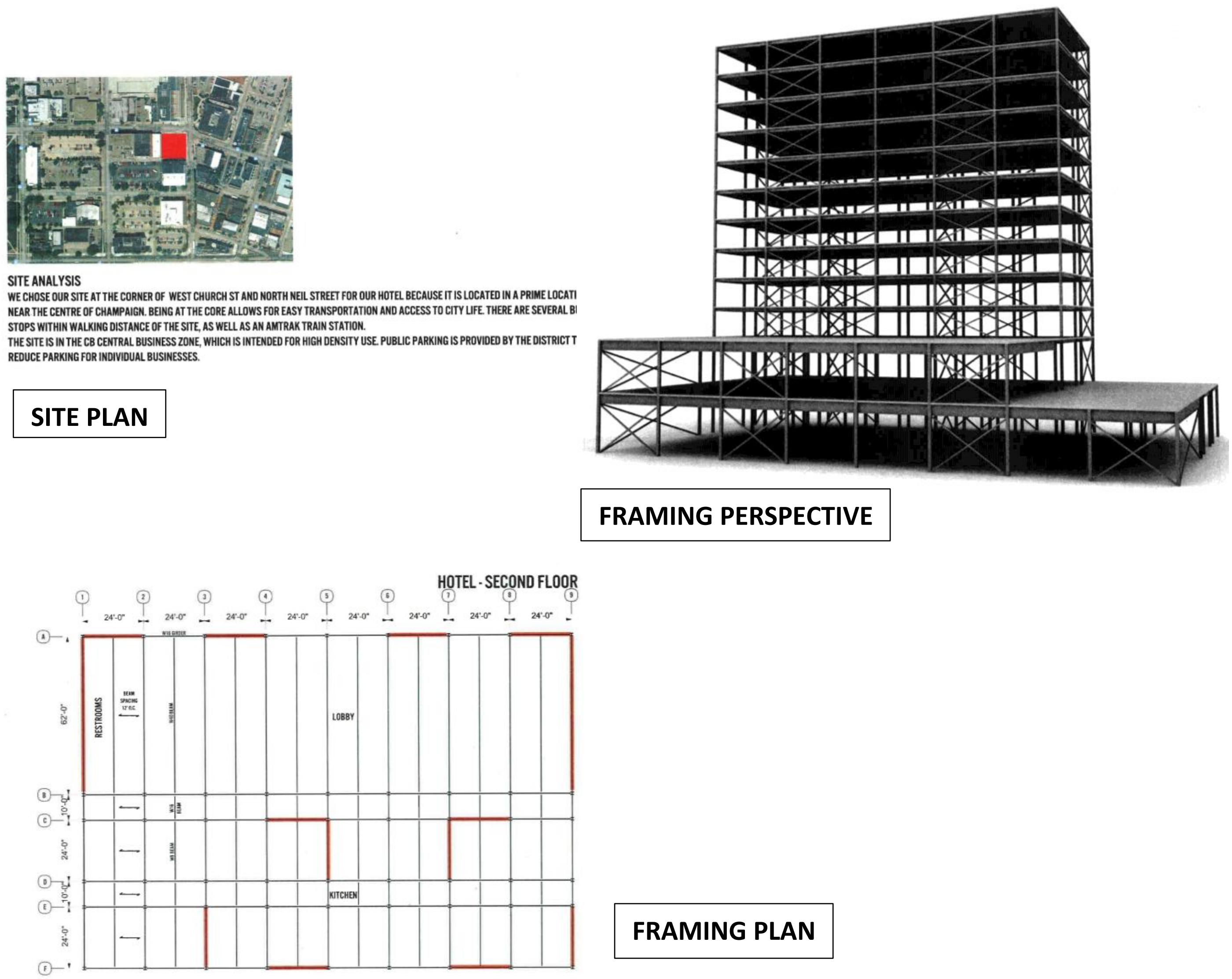

Figure 2: Sample Project Graphics

Lessons Learned

The authors taught a total of three sections of this course, with approximately 90 students, in Fall Quarter 2013. It will be taught again in Winter Quarter 2014. Several lessons were learned in the Fall Quarter that will be incorporated into the Winter Quarter classes. The primary conclusion was that we tried to include too much content and that more time needed to be spent on building configuration issues. This will be addressed in several ways. The calculational content of the course will be reduced, somewhat. The intent is to make it more focused and to apply more directly to the configuration issues. The Winter Quarter classes will also be reorganized somewhat. The Fall Quarter courses were organized into small building and large building modules, reflecting the two original courses that this course replaced. Consequently there were two projects and two midterms. In the Winter Quarter, structural systems using all three materials will be presented in the first half of the course. One midterm and one project will be eliminated. The second half of the course will be devoted to configuration issues and the single project. It is hoped that this new arrangement will be more efficient and allow more time for practice of configuration issues. Concentrating the calculational material in the first half of the course has also been a popular approach for the ARCH and CM students. The deletion of the first project will require that additional review time be invested in homework and the remaining project to insure that students understand expectations for the products and acquire the skills needed to prepare them.

Conclusions

Architecture and construction management students can often graduate with a weak foundation in structural engineering leaving them less than fully prepared to take on their future roles in industry. The Architectural Engineering Department at XX University offers a sequence of five support courses taken by architecture and construction management students that gives them a solid grounding in statics, properties of materials and structural systems. The five course sequence has been recently reconfigured in response to requests by the ARCH and CM Departments. This required the compression of the material previously covered in two courses into a new single new course. Several sections of this new course were taught in Fall Quarter 2013 and several lesson learned that will be incorporated into the Winter Quarter course. This compression resulted in reduced depth of some of the material and an elimination or relocation of other material. Still it was believed to represent a good balance of content and will provide the students with a strong background in structural engineering knowledge and skills.

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