New Capstone Design Course Combining Architectural and Engineering Aspects of Building Design

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Abstract

A new "Capstone Design" course, titled "Innovative Sustainable Residential Design," is developed by the authors and is team taught at University of California, Berkeley, for the first time during the Spring Semester 2016. The format of the course as well as the way it is taught introduces innovative pedagogy and technology, including (a) the course syllabus that presents a balanced coverage of structural engineering, architectural design, zero-net-energy, sustainable design, and ethical issues in design; (b) two faculty members, one from the Department of Architecture and one from the Department of Civil and Environmental Engineering, teach the course; (c) the course is taught in one of the "design studios" in the Jacobs Institute for Design Innovation, which is a modern facility similar to a modern architectural/engineering (A/E) design office, that houses laser cutters, CNC routers, and a variety of low- and high-end 3D printers; (d) the course has no exams or traditional homework, but coursework comprises Research Papers, Design Assignments, an Ethics Paper, Progress Reports on Student Term Design Project, and a Final Design Report, (e) students from both architecture and engineering are encouraged to enroll, (f) leading experts in architecture, structural engineering, zero-net-energy design, and sustainability give invited lectures followed by discussion sessions; and (g) students are organized into teams to work on their Term Project.

This course introduces three important innovations to the classroom: (i) student teams not only design but also make architectural and engineering computer models, as well as 3D rapid prototypes of their designs; (ii) professors from two different disciplines teach the course and engages the entire faculty of both colleges by including guest speakers, reviewers, and critics; and (iii) the co-professors run the course more like a design studio, with direct and individual contact with the students, and act more like coaches rather than the traditional "sage on the stage" teachers.

Introduction

One may ask why so many of the great buildings from antiquity, in virtually every culture, appear as a holistic form where the structure and the architecture are both innovative and integrated. Is it because the designers and builders actively strived to integrate their two disciplines, or is it because they had not yet been separated? Pondering this question, the authors embarked on an experiment in education. The idea was to take junior and senior students from the Department of Architecture and the Department of Civil and Environmental Engineering and place those students in teams, who were tasked with designing an innovative, integrated, and net-zero energy building for the 21st century. The course would be co-taught by one professor from architecture and one from engineering, and all discussions and work sessions would occur in a studio environment with adjacent maker spaces that supported 3D printing, CNC routers, and laser cutters. The studio was housed at the newly opened Jacobs Institute for Design Innovation at UC Berkeley. Dr. Paul Jacobs, who is the major supporter of this initiative, when announcing the establishment of the Jacobs Institute, stated that:

> *"Today, it is not enough to provide our future engineering leaders with technical skills. They must also learn to work in* ***interdisciplinary teams,*** *how to* ***iterate designs rapidly,*** *how to* ***manufacture sustainably,*** *how to* ***combine art and engineering,*** *and how to address* ***global markets****...to create our future."*

This course was developed to realize the above vision. More information on the Jacobs Institute can be found at http://jacobsinstitute.berkeley.edu/.

The premise of this course was the concept that a better building would result if the architecture and the engineering were considered together from the beginning of the design process. This approach is significantly different from current practice, where an architect is tasked with generating a design, and an engineer is then expected to apply mathematics to make it stand up. By the time the engineer becomes involved, many design decisions have already been made, and the architect is committed to those decisions. As a result, the current model lends itself to confrontation, because any design modifications proposed by the engineer, although helpful, are seen as an infraction of the original architectural design.

The model we propose considers the design from the perspective of a master builder, where architecture, structure, construction, and the modern necessities of being energy efficient, are equal components of a *design process*. In this scenario, the structure is considered at the very beginning along with architectural sketches. At the same time that physical models are being contemplated, structural computer models are being generated. This allows both disciplines to influence the design. A modification in the structure that improves its performance can then be examined in a physical or sketch-up model to understand the impact on the architecture and vice-versa. A modification in the architectural model can be considered in the structural model to understand the impact on the structure. The goal of these iterations is to arrive at a synergy between the architectural design and structural integrity. While this integration was our primary goal, other objectives include emphasizing sustainability, construction practices, and professional ethics.

The course was offered first in the spring of 2016 as a 3-unit elective course in civil engineering and as a 3-unit elective course in architecture. The architecture students wishing to take the course enrolled in Arch-159. Similarly, engineering students wishing to take the course enrolled in CE 190, which is a new course created by the first author (A. Astaneh-Asl). The goal of this course is to engage students in not only structural design but to enable structural engineering students in civil engineering to work intimately as members of an architectural and engineering (A/E) team, simulating real-world conditions upon graduation. The course will become a "Capstone" design course as defined by the ABET (Accreditation Board for Engineering and Technology.) The long-range goal is to have the course listed as an elective course in the Department of Architecture and as a capstone design course in the Department of Civil and Environmental Engineering. During its first offering, the course attracted six architecture students and 20 engineering students (fifteen of whom were majoring in structural engineering, four of whom were majoring in environmental engineering, and one student majoring in mechanical engineering).

Course Syllabus and Who Should Be Enrolled in this Course?

The course is a 3-unit course that meets for 75 minutes, three times a week, for a total of 4.5 hours of student contact time per week. Two meetings are called "Lectures," and the third one is designated as the "Laboratory" section. Although designated as "lectures," there are no formal lectures in this design course. During "lecture" hours, both professors, as well as the Graduate Student Instructor (GSI), work in the studio with student teams and discuss various aspects of the design. The third 75-minute session, the "Laboratory," is designed for student teams to work with the GSI on their project.

For this first time offering, the course was open to juniors and seniors and also to graduate students. Most students in class were juniors or seniors, with two graduate students from the Department of Architecture. Based on the experience gained this semester, the course should be limited to seniors only. The interaction of graduate students with the other members of the design team who were undergraduate students was problematic. Also, in regards to the civil engineering students, only seniors should be allowed to enroll. This was because the skill set needed requires that engineering students have been exposed to engineering design courses. Juniors were unfamiliar with higher level analyses, which included finite element modeling using computer software programs such as SAP.

The students at the end of the semester were required to prepare a final report and make a team presentation of their work to the class before a panel composed of the two professors and an expert on net-zero energy design and sustainability. The final report included an explanation of architectural design decisions, structural engineering methodology, sustainability, and zero-energy aspects, as well as construction details and how the design interacts with the community.

Formation of the Design Teams

Teaming is "the engine of organizational learning," [1] and design, as we taught it in this class, is fundamentally a learning process [2]. Thus, one of the keys to the success of the course is how to organize the project teams. The students were not assigned to individual teams until the third week of class; this gave the students time to get to know one another, allowing them to form teams more naturally. Another key factor would be to require disciplinary diversity on the teams, which in this case meant that each team must contain at least one student from the Department of Architecture and one student from the Department of Civil and Environmental Engineering who was majoring in structural engineering. This dictated that six was the maximum number of teams possible, which was limited by the number of enrolled students from architecture.

On the day the teams formed, it was announced that it was mandatory that each team contain one architecture student and at least one structural engineering student, with a maximum number of 4–5 students per team. The process of devising the teams began by positioning one architecture student at each of 6 tables and then allowing the remaining students to sort themselves into table groups; this took roughly 30 minutes. We believe that this simple approach to team building with the disciplinary diversity critical to project completion was so crucial to the success of the course that we felt it necessary to highlight this process herein.

Team projects are often challenging for students and faculty alike. The many potential pitfalls include students not getting along; students taking advantage of the team grading scheme and allowing their teammates to do most of the work; teams struggling to create a shared goal for their work; and mis-communication. Teams working on complex design projects—such as the one compiled in this class—required an appropriate degree of "psychological safety" [1] to feel comfortable in sharing ideas, giving and receiving meaningful feedback, criticizing the status quo, and making mistakes. We were concerned about these problems especially in a multi-disciplinary design course, where conflicts over design priorities, opinions, and aesthetics are bound to occur.

Upon observing the teams, however, we found that the teams got along well, worked well together, and most members pulled their weight. We held weekly desk critiques, focusing on both structural and architectural issues; in the later weeks, these critiques included sustainability and construction practices. From these critiques and face-to-face work with each student, it was possible for the instructors to assess each team's workflow. Throughout the semester, the workflow appeared exceptional and work-distribution equal. We did not observe disharmony in any of the teams. During the weekly critiques, we saw cooperation at a level we had not experienced in other team-based courses. One of the reasons for this may be the result of implicit norms of hearing from everyone. In the case of disagreement, 'the expert' could be consulted. For example, whenever a structural engineering question arose, all students provided welcomed input, but they allowed the structural engineering student to have the final say. Likewise, whenever an architectural issue came up. All students verbalized their opinions, but they tended to respect the architecture student in the group and in the end deferred to that student's judgment.

Although the distribution of the workload seemed equitable at the beginning of the semester, toward the end of the semester we were approached by two students from one of the teams who complained that their other team members were not contributing an equal share of the workload required to prepare the final presentation. As a result, we sought help from the co-founders of the UC Berkeley "Teaming with Diversity" program, Sara L. Beckman and Barbara Waugh, who have integrated teaming content into a broad range of project-based courses across the Berkeley campus. The modular content of their program allowed us to use an online survey that collects anonymous peer evaluations from the students about their own and their teammates' contributions to the team. The complete program includes approaches for forming diverse teams, materials to launch teams, mid-term check in evaluations and tools for debriefing them, and end-of-semester assessments. In this class, only the end-of-semester evaluations were used. Students were asked to provide a sentence each about the contributions they and their teammates made to their project, and then allocate 100 points divided among themselves and their teammates to represent relative contribution. Students received data in return that showed how they perceived their contribution and how their teammates' viewed that contribution. This allows the faculty to receive data that provides them with the bigger picture for each team, which is often better than engaging in "he said – she said" discussions with the students.

We were surprised to see the survey's results, which showed that there were underperforming students on two of the teams; one team had two underperformers by the team's reckoning. This was in sharp contrast to the levels of team cooperation and workflow we observed throughout the semester. The survey data, however, provided useful comments, such as "did not produce quality work" or "attempted energy analysis but was not accurate." It is possible that (a) such difficulties did not surface in our in-class discussions, or (b) these problems occurred in the final two weeks of the class when students were preparing the final presentation for this class along with work for other courses.

Regardless of the reason, we wonder if the 'cracks' in the teamwork could have been avoided with more emphasis on team dynamics throughout the semester. Including a "collaborative plan" outlining goals, roles, processes, and relationships might have helped students get on and stay on the same page throughout the term. Using earlier and more frequent peer feedback mechanisms, such as surveys or "stop-keep-start" team assessments, might have highlighted concerns so they could be dealt with sooner. Thus, we aim in future offerings of the course to embed more of the "Teaming with Diversity" curriculum to support our students through their intricate design work.

The Team Project

Successful completion of the team project required a team of four or more students. The workload would be too much for a 3-unit course with smaller teams. The semester-long project, which culminated in a final presentation, required each team to design and engineer a net-zero energy housing unit consisting of between two and three stories and between four and eight individual units. All teams worked on the same site located in a residential area of Berkeley that was zoned for multifamily housing. The lot was vacant but was being used as a community garden. Each team had to design a residential complex that could accommodate four to eight condominium units. One team elected to design a youth hostel with a community kitchen and separate and communal living accommodations. We approved this change in scope. The other teams stayed true to the original architecture assignment.

The structural system for the architecturally designed building included the design of the superstructure and the foundations. Each team had to consider construction systems in the overall design to achieve net-zero energy. Most teams chose steel moment frames; i.e., steel braced frames and wood framing with shear walls as their primary structural/construction system. To achieve net-zero energy, students considered orientation, shading devices, and lighting systems, and also included enough usable roof area for solar thermal panels and photovoltaic panels. Each team also examined the interface with the community, addressed construction issues, sustainability, zero energy considerations, and the interaction of the designed building with the surrounding community. In the following sections, the activities on each of these inter-related design considerations are discussed, with examples of how each team addressed these specific design considerations.

Course Content

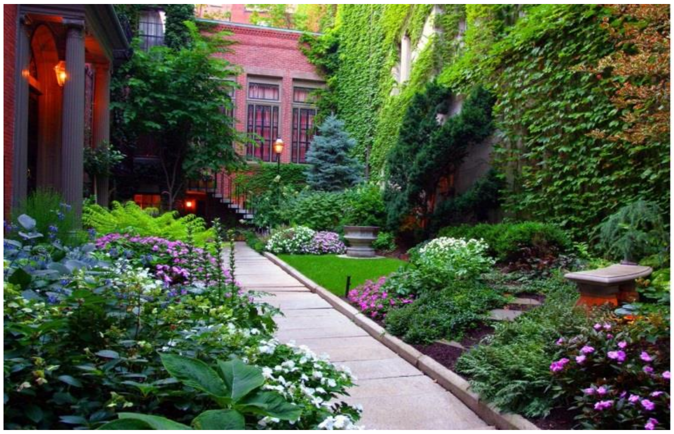
While the course was interdisciplinary and intentionally blurred the traditional lines between those disciplines, there were nevertheless two broad headings of the course -- Architecture and Structural Engineering. Under each of these, there were sub-headings. Under Architecture, we included “interface with the community” (which had an ethical component to it) and “sustainability,” which focused on the use of materials and designs necessary to achieve net zero energy for the project. Under Structural Engineering, we included “foundation design” and “construction methods and materials” (which also contained a sustainability component).

The Architectural Design

The most daunting part of this section was how to introduce engineering students to architecture and architectural design in short order and in a way that would enable them to engage in the process so they would be able to make valuable contributions to the architectural design. In week two, we introduced students to *A Pattern Language* (APL) [3]. After selecting 17 patterns that would be most relevant for their project, they were asked to develop a “project pattern language” to help direct their design. Preparation of the project pattern language was assigned as an individual task (one of the research papers students completed during the term). For this assignment, they were required to read each pre-selected pattern and re-write it in shorthand, pulling out the essential points. They were also required to choose a new photograph that they felt was archetypical of each of the patterns. They were also asked to pick a few new patterns that they thought might have applicability to their project and complete the same tasks described above.

This assignment had a powerful impact on the project. Because the original APL is written from a humanistic point of view where the main point of architecture is to respond to human needs, physically and emotionally, it was relatively easy for students who have not been trained in the arts to connect on an intuitive level. Once they read each of the selected patterns, it made sense to them. The engineering students could easily put themselves into the described situation and understand and react to it without needing years of exposure to architectural theory or even architectural history. As an example, take pattern number 112 Entrance Transition. The pattern begins with a problem statement;

Buildings, and especially houses, with a graceful transition between the street and the inside, Figure 1(a), are more tranquil than those, which open directly off the street, Figure 1(b).



(a) (b)

Figure 1: (a) A Graceful Transition between the Street and the Inside; and (b) An Abrupt Entrance – No Transition.

It then continues with an argument, giving positive and negative examples:

The experience of entering a building influences the way one feels inside the building. If the transition is too abrupt, there is no feeling of arrival, and the inside of the building fails to be a sanctum.

The following argument may help to explain it. While people are on the street, they adopt a style of "street behavior." When they come into a house, they naturally want to get rid of this street behavior and settle down completely into the most intimate spirit appropriate to a house. However, it seems likely that they cannot do this unless there is a transition from one to the other which helps them to lose the street behavior. The transition must, in effect, destroy the momentum of the tension and "distance" which are appropriate to street behavior, before people can relax completely.

The pattern ends with a solution statement and a graphic representation of the essential points:

Make a transition space between the street and the front door. Bring the path which connects street and entrance through this transition space, and mark it with a change of light, a change of sound, a change of direction, a change of surface, a change of level, perhaps by gateways which make a change of enclosure, and above all with a change of view, Figure 3.

It is easy to see how an engineering student (or anyone else for that matter) could understand all aspects of the pattern because they can “feel it” and determine for themselves if it makes

Figure 2: Each Example Creates a Transition with a Different Combination of Elements.

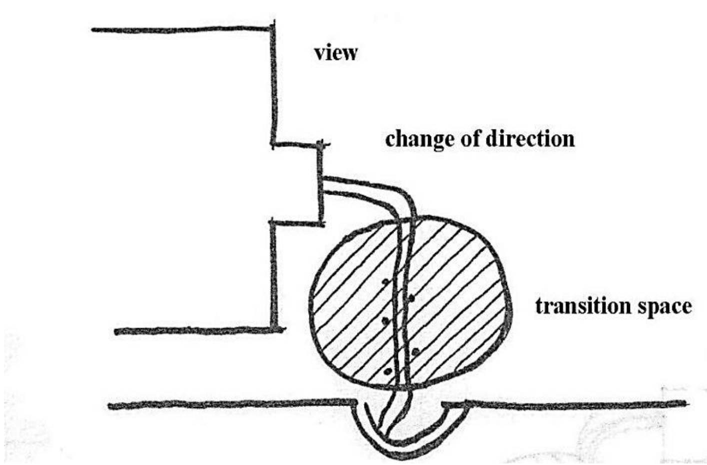


Figure 3: Sketch of Solution.

sense. Once the mental connection is made, they are given a solution statement, some examples, and a graphic to help them engage in useful dialogue about this particular design element in their project. When one considers the rather extensive list of patterns required for study, it is no accident that the engineering students became major contributors to the architectural design process. In one of the teams, the architectural student specialized in building science, not design. For this team, the architecture was devised by the team without a team architect. Moreover, for all teams, heated discussions occurred among the students during their design sessions. Figure 4 shows student work on the A-Pattern-Language assignment.

This assignment also had the effect of putting team members on more of an equal footing with the architecture student. While most team members tended to defer to the architecture student for much of the graphical portion of the design, such as Sketch-up models, plans, and sections, other students were still active participants, and the final architectural result was most definitely a joint team effort.

The final report had a section on architectural process, which included an explanation of architectural design decisions they had made, In addition, they submitted architectural plans, including a site plan, sections, elevations, and a 3D computer model along with a 3D rapid prototype physical model. One camera shot of the computer model was selected for rendering. Figure 5 shows architectural renderings of the six teams.

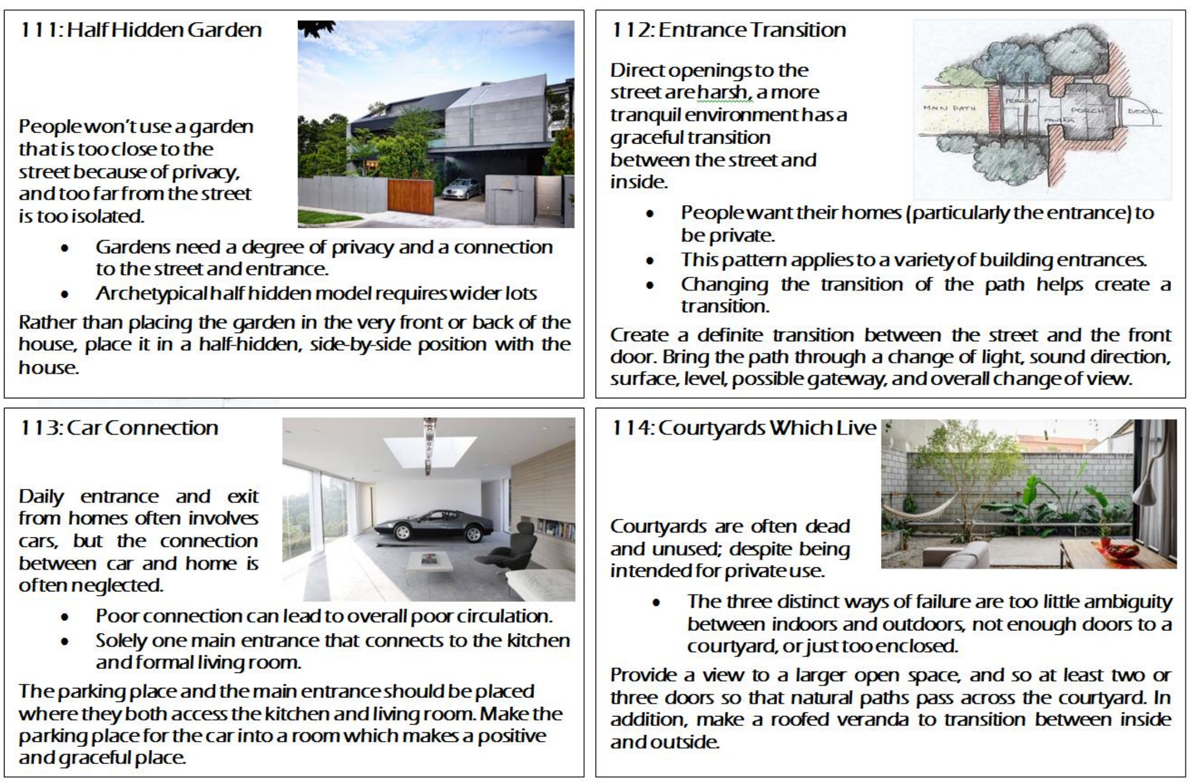


Figure 4: Student's Work on the Pattern Language Assignment.

Interface with the Community

Each team worked on the same site located in a residential area of Berkeley, California, about two miles from the campus. It was a vacant lot with a tall (1.5 story) youth center on the south side and a tall single-story storage building on the north. The lot fronted on a residential (Bonar) street to the west and a community park to the east. At the time the project was assigned, the site was fenced off on the east and west, and was planted in vegetables, which were part of a community outreach program with the youth center. Only community members associated with the garden could enter to the site.

Early on, some students expressed concern with the site chosen, given that they would be siting their building onto a community garden. This caused an ethical dilemma among the teams. Most teams dealt with this aspect of the project by making design decisions that endeavored to interface with the community. One team created a series of gardens on the ground floor and made the site permeable from Bonar Street through to the community park, allowing the community to use their site for access to the park. This resulted in potential security issues for the new residents that the team had to address. Another team built their condominiums as platforms in a structural steel tree, keeping the original ground plane free and clear of a building footprint, and treading as lightly as possible on what they considered hallowed ground. By placing all of their units up in the air and parking underground they were able to keep most of the original site accessible to the community for use as a garden. Some square footage was required for the base of the "trunk" and a path that leads to the base of the trunk; the design called for a private stair and elevator, which allowed the community onto the property but addressed issues of privacy and security for the residents.

Figure 5: Architectural Renderings of Six Team Designs

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Energy and Sustainability Issues

The only required textbook for the course was Ref. [4] by Ann Edminster on zero energy. Each team was required to prepare an annual KWh (kilo-watt-hour) demand using published data for space heating and cooling in the applicable climate zone and published data from manufacturers of appliances with estimated usages for a typical American family. From this research, the teams estimated the size of a PV array (photovoltaic array) and solar water heater to assist in determining locations and areas required to accommodate the hardware. In addition to the team design project as outlined above, each student was responsible for completing three research papers; one which addressed architecture, one which addressed structural/construction systems, and one which addressed professional ethics.

This part of the project required teams to think about the materials selected for construction: where they were sourced, how renewable they were, how much carbon gas their manufacture generated, and their durability. As part of the requirement that the buildings had to be net-zero energy—meaning that they had to generate all of the power on site—students had to consider materials and designs that provided insulation, prevented or reduced thermal bridging, reduced solar insolation, and generated electricity and heated water. A wide variety of designs and techniques were explored. These included green roofs over living spaces used as a private outdoor space for the units above, special glazing that reduced heat gain and generated electricity, solar hot-water heaters and ground source heat pumps, brie solei's (which provided sun shading and generated electricity), and a glass wall designed so that water could run through it, thus cooling it down at night through emissive cooling and collecting heat during the day, to name a few.

Students were specifically encouraged to propose (and design) solutions that are still in their infancy and years away from implementation. Students were required to calculate their annual demand load from space conditioning, appliances, and hot water generation, and then calculate the amount of area needed to provide room for power-generating apparatus, such as photovoltaic panels and solar hot-water panels. One of the team members either volunteered or was assigned (by the other team members) to become the "expert" and direct this part of the design work.

Structural Design

Each team had to design the structural system to resist gravity and lateral loads, i.e., the team had to design a complete building structure and prepare a SAP (structural analysis program) [5] finite element model of their design. Based on the SAP results, they were required to perform stress checks on their structural members and size them. As stated earlier, students performed several SAP iterations to bring the structure and the architecture into alignment. As part of the final presentation, each team was asked to prepare a framing plan and details of the main structural connections. They also had to design the connection to the ground and design a foundation; see the next section. Figure 6 shows examples of structural models and stress analysis.

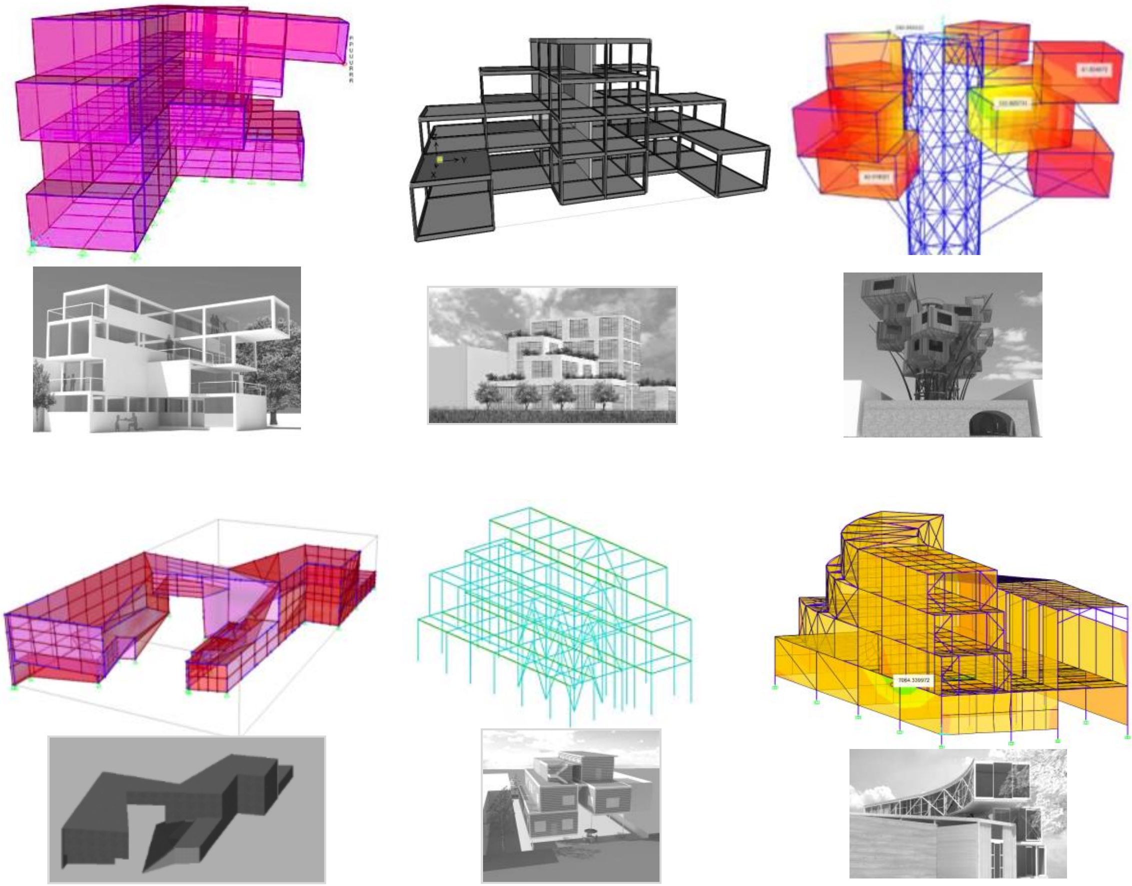

Figure 6: SAP Model of Framing Systems [5].

The teams were asked to build a structural model of their building using the SAP structural analysis program [5] and design the structural framing to support gravity dead and live loads. Because this course was being offered for the first time, we were concerned that requiring the teams to perform a seismic design would impose a significant amount of structural engineering work beyond what a 3-unit course should require. We were also concerned that some students may not have been exposed to the concepts of seismic design and earthquake loading in other courses, thus requiring a significant amount of lecturing to provide the necessary background. However, we announced that if any team wanted to perform a seismic design of their buildings, we would assist them so they could present the results in their final report. Two teams had members who were familiar with the design software SAP, and they chose to perform a seismic design for their structure. The other four design teams that did not conduct a full-fledged seismic design were required to develop a lateral load-resisting system in their structural model to resist the wind and lateral seismic loads. Of the two teams that did perform a seismic design, one chose base isolation [6], which was an appropriate choice given that their very rigid framing system was made of vertical and horizontal trusses and X-bracing. The other team chose to use a traditional lateral force resisting system since their framing system was relatively flexible moment frame system not suitable for base isolation. Figure 7 shows the SAP model for the structure that used base isolation in their seismic design.

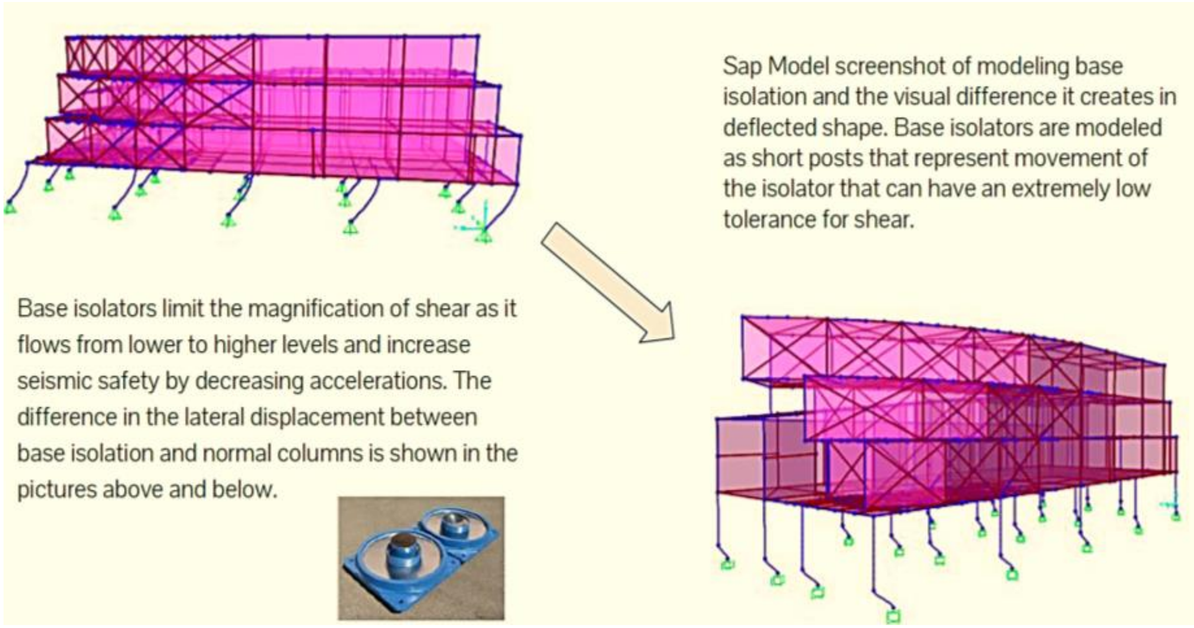

Figure 7: One Team Used Base Isolation in Seismic Design, Demonstrating Significant Reduction in Seismic Forces [6].

Foundation Issues

It was specified that the building be located in the flat lands of the City of Berkeley, but no specific soil condition was given. The teams could decide what type of soil conditions might exist under their designed building and thus were tasked with designing a proper foundation system for that soil condition and applied loads. The teams considered the soil to be dense soil or soft soil. Depending on the assumption made, the foundations selected were spread footing or mat foundation, or, in one case, pile foundations.

Construction Issues

Each team was required to propose a construction scheme and construction materials, and draw a typical wall section showing the connection of the foundation to any intervening floors and the roof. Also, the teams were expected to study the construction sequences and make recommendations on how their designed building will be constructed.

The material used in construction could be traditional wood, steel, or concrete, a combination of these materials or other historical material (such as brick or adobe) as well as modern and innovative construction materials (such as straw-bale construction or fiber-reinforced polymer composites). One of the tasks early on in the semester was for students to research and collect publications on the various materials used in the construction of homes throughout the history, starting with cave dwellings, adobe homes, and then moving into more modern materials, such as steel, aluminum, reinforced concrete, and fiber-reinforced polymers. Students using the collected information had to write a Research Paper on the advantages and disadvantages of each of the construction materials.

Conclusion

1. The course gives architecture and engineering students the experience of working together in a collaborative environment—an environment where both disciplines are valued and appreciated for what each one brings to the design table. By having architecture students work closely with engineers, they learned some of the tasks that engineers perform in the pursuit of the structural design and gain a much greater understanding and appreciation for engineering methodology. Conversely, by requiring engineering students to participate in the creative side of a design (that will later form the basis of the engineering work); they can acquire an appreciation for design concepts that go far beyond the mechanics of structural integrity. It is the hope and belief of the instructors (i.e. authors) that this exposure will lead to a more holistic working environment for both professions, ultimately resulting in a built environment that is more economical, sustainable, and healthy.
2. Although the course could theoretically be taught by a single faculty member, for example, an architecture professor with knowledge of engineering design or an engineering faculty with knowledge of architectural design, it is our recommendation that the course be co-taught with two faculty members—one from each discipline. Co-teachers from the different disciplines provides students with firsthand knowledge of the relationship and conflicts inherent between the two disciplines.
3. The pattern language paper and the ethics paper are indispensable for two reasons: (i) allows the engineering students to engage in the early architectural design work and (ii) introduces students to professional ethics and has them realize the importance of ethical conduct in design.
4. The selection of special topics and the speakers chosen to speak on these topics is an important part of the course that we feel was not perfectly orchestrated in this first offering. We plan to give this more careful thought in future course offerings.
5. Finally, it is extremely important to assess how the internal dynamics of the teams early on and throughout the entire semester to insure that each member is pulling their fair share of the work load, and that the team work is greater than the sum of the team members.

Acknowledgments

On the final day of class, one week before the final project presentation was due, we asked the students to share their experiences with us and make recommendations about what they would change in a future offering of the course. Their comments were thoughtful, sincere, and extremely helpful. As we move into a second offering of the course next year, these comments will be referred to over and over. This invaluable input is sincerely appreciated. Professors Barbara Waugh and Sara Beckman of UC Berkeley were invaluable in helping us (1) assist students to improve their "teamwork skills" and (2) conduct a survey at the end of the semester to assess student collaboration and participation. Their work was very helpful, and we sincerely appreciate their time and the valuable results gleaned from their teamwork survey. The authors would also like to express their sincere appreciation to Claire Johnson for her excellent editing of this manuscript. The support of Emily Rice and Amy Dinh at the Jacobs Institute for Design Innovation at UC Berkeley is much appreciated.

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