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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 the University of California, Berkeley, for the first time during the Spring Semester 2016. The format and the manner in which the course is taught introduce 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 teach the course, one from the Department of Architecture and one from the Department of Civil and Environmental Engineering; (c) the course is taught in one of the "design studios" in the Jacobs Institute for Design Innovation—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 comprising 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 collaborate on their Term Project.

This course introduces three important innovations to the classroom: (i) student teams design, devise architectural and engineering computer models, and create 3D rapid prototypes of their structural designs; (ii) professors from two different disciplines teach the course and engage 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, to 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 civil/structural 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 is the major supporter of this initiative and when announcing the establishment of the Jacobs Institute, he 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. Herein, *better* is defined as a cohesive design that incorporates state-of-the-art sustainable practices, engineering principles, and community involvement. 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 proposed model 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 structural system 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 zero-energy design, sustainability, best 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. In the next offering, the course will be a *Capstone Design Course.* 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) design team, simulating real-world conditions many of them will work in 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 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 and 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, seniors, and 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. Regarding, 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 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 is requiring 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 the maximum number of teams possible was six, 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. The authors 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 the authors 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 struggle to create a shared goal for their work; and miscommunication. 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. The authors were concerned about these problems especially in a multi-disciplinary design course, where conflicts over design priorities, opinions, and aesthetics are bound to occur.

In general, the authors in teaching this course found that the teams got along well, worked well together, and most members pulled their weight. There were 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 (i.e. the authors) to assess each team's workflow. Throughout the semester, the workflow appeared exceptional and work-distribution equal. The instructors did not observe disharmony in any of the teams. During the weekly critiques, the authors saw cooperation at a level they 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 students 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 the authors 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, the authors 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.

The survey's results showed that there were underperforming students on two of the six design teams; one team had two underperformers by the team's reckoning. This was in sharp contrast to the levels of team cooperation and workflow that the authors 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 the 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, the authors wonder if this breakdown in the teamwork could have been avoided if there had been 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 semester. 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, the authors aim in future offerings of the course to embed more of the "Teaming with Diversity" curriculum to support the students through their intricate design work.

The Team Design Project

Successful completion of the team design project required a team of four or five 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 before a panel made of the two faculty members (i.e. the authors) and a zero-energy design expert (i.e. Dr. Ann Edminster) and to the class, required each team to design and engineer a two- or three-story high net-zero-energy housing unit, with between four and eight individual units. All design teams worked on the same site located in a residential area of Berkeley that was zoned for multifamily housing. The lot is vacant but is currently 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. The authors approved this change in scope. The other teams stayed true to the original architecture assignment.

The structural system for the architecturally designed building included designing 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, lighting systems, and 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 design 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, the authors as instructors of the course 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, the authors included “foundation design” and “construction methods and materials” (which also contained a sustainability component).

The Architectural Design

The most daunting part of this activity was how to introduce engineering students to architecture and architectural design in a limited time frame 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, the authors as instructors of the course 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.

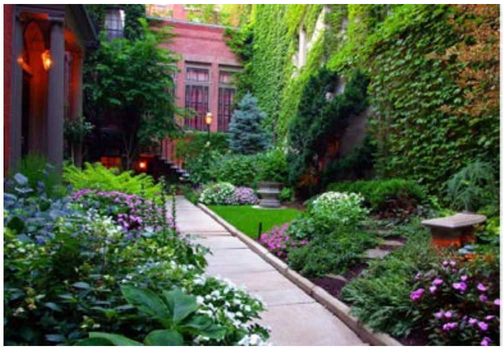
This assignment had a powerful impact on the project. Because the original APL is written from a humanistic point of view where the main point of architecture is to respond to the physical and emotional needs of the inhabitants, it was relatively easy for students who have not been trained in architecture to connect on an intuitive level. Once they read each of the selected patterns, 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 done by a student team in the course. 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,”*[3] Figure 1(b).

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, Figures 2 and 3.” ([3], Page 539)



(a) A Graceful Transition between the Street and the Inside

(b) An Abrupt Entrance – No Transition.

Figure 1. Two Different Transitions between the Street and the Inside

A common path provides an entrance transition to a group of building entrances

Figure 2. Example of Transition with Different Combination of Elements

(a) Entrance transition along a path and through a wooden gate.

(b) Entrance transition over a foot bridge winding through a garden

(c) Entrance transition through an arch into a courtyard.

Figure 3. Three More Examples of Transition with Different Combination of Elements

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,*" [3], Figure 4.

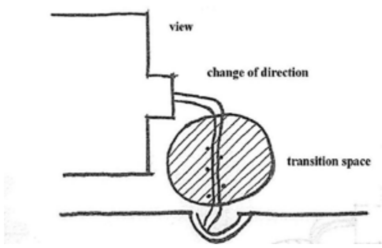


Figure 4. Sketch of Solution

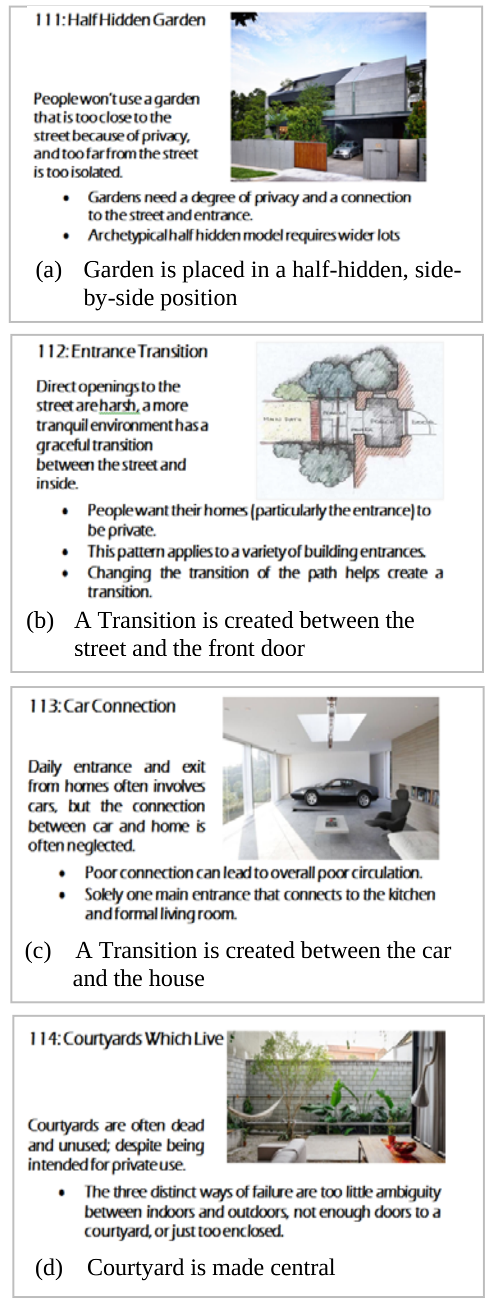
It is easy to see how an engineering student (or anyone else for that matter) could understand all aspects of the pattern because they can "feel it" and determine for themselves if it makes sense. Once the mental connection is made, they are given a solution statement, some examples, and a graphic to help them engage in useful dialogue about this particular design element in their project. Considering 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 5 shows student work on the APL 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 contained (1) a section on the architectural process, which included an explanation of architectural design decisions they had made; (2) the architectural plans, including a site plan, sections, elevations; and (3) a 3D computer model along with a 3D rapid prototype physical model. One camera shot of the computer model was selected for rendering. Figure 6 shows architectural renderings of the six team designs.

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 is 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 fronts 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 the site.



(a) Garden is placed in a half-hidden, side-by-side position

(b) A Transition is created between the street and the front door

(c) A Transition is created between the car and the house

(d) Courtyard is made central

Figure 5. One Student Team's Work [4] on the Pattern Language Assignment

Figure 6. Architectural Renderings of Six Team Designs

Some students expressed initial concern with the site chosen, given that they would be placing 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 to tread 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.

Energy and Sustainability Issues

The only required textbook for the course was *Energy Free-Homes for Small Planet* by Ann V. Edminster [5]. Each team was required to prepare an annual kWh (kilowatt-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 that addressed architecture, one that addressed structural/construction systems, and one that 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) innovative 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 finite-element model of their design. In building the structural model, the students used the SAP2000 structural analysis software [6]. Based on the results of finite element analysis, the students were required to perform stress checks on their structural members and size them. As stated earlier, students performed several finite element analysis 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 7 shows the structural finite element analysis models for all six team designs.

Because this course was being offered for the first time, the authors were concerned that requiring the undergraduate student teams to perform a seismic design would impose a significant amount of structural engineering work beyond what a 3-unit course should require. the authors, as instructors of the course, were also concerned that some students might 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, the authors announced that if any team wanted to perform a seismic design of their buildings, the authors would assist them so they could present the results in their final report. Two teams had members who were very familiar with the finite element analysis and design software SAP2000 [6], 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 using *Friction Pendulum™ Bearings* [7], which was an appropriate choice given that their very rigid framing system was made of vertical and horizontal

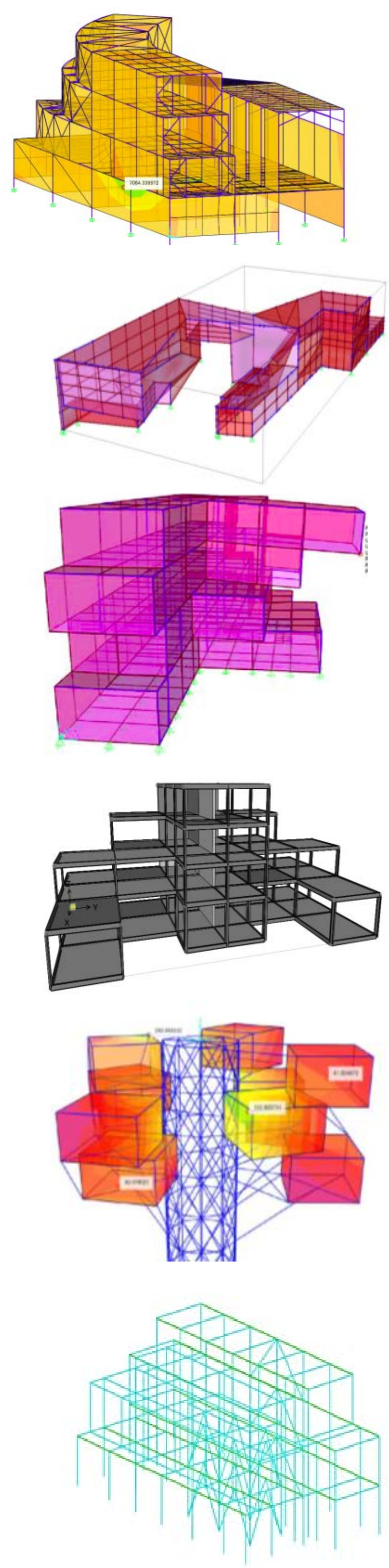
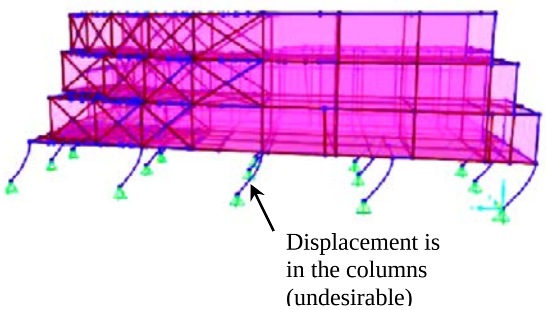
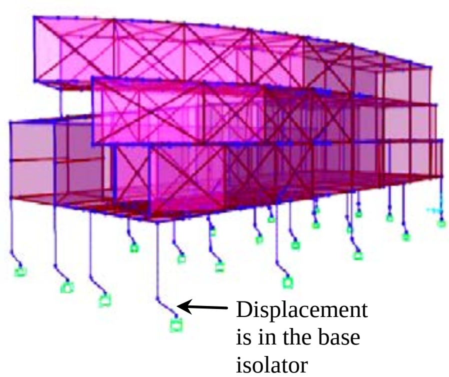


Figure 7: Finite Element Models of the Six Team Designs

trusses and X-bracing and had very high stiffness. The other team chose to use a traditional lateral force-resisting system since their framing system was a relatively flexible moment frame system not suitable for base isolation. Figure 8 shows the finite element analysis model for the structure of the design team that used base isolation in seismic design



(a) Seismic analysis model of the structure **without** base isolation showing large lateral displacement. The structure had large seismic forces too.



(b) Seismic analysis model of the structure **with** base isolation showing reduced lateral displacement.

Figure 8. One Team's Analysis Model without and with Base Isolation [4]

Foundation Issues

Although the design challenge specified that the building is located in the flat lands of the City of Berkeley, 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. The purpose of this assignment was to have students research and collect information on various building construction material and discuss the pros and cons of each material in terms of mechanical properties, cost, sustainability, durability and eventual demolition and recycling.

Conclusion

1. The new course discussed in this paper provides architecture and engineering students the experience of working together in a collaborative environment—an environment where both disciplines are valued and appreciated for the assets each discipline 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 design, 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 authors, who developed the course and taught it for the first time, that this exposure will lead to a more holistic working environment for both professions, ultimately resulting in a built environment that is more economical, energy efficient, 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 a structural engineering faculty with knowledge of architectural design, it is authors' recommendation that the course is co-taught, with one professor from architecture and one professor from structural engineering. 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 book and the ethics paper are indispensable for two reasons: (i) it provides a crash course in architectural theory so that engineering students can engage from the beginning in the preliminary architectural design; and (ii) it introduces students to professional ethics that emphasizes 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 the authors feel was not perfectly orchestrated in this first offering. The invited speakers were from architecture, zero-energy design, structural engineering, and engineering ethics fields. The authors plan to give this more careful thought in future course offerings and invite experts from construction and sustainability fields as well.
5. Finally, critical assessment of the internal team dynamics should occur early on and throughout the entire semester to ensure that each member of the student design teams is pulling his/her fair share of the workload and to emphasize that the teamwork is greater than the sum of the team members' work.

Acknowledgments

On the final day of class and one week before the final project presentation was due, the authors, as instructors of the course, asked the students to share their experiences and make recommendations about what they would change in a future offering of the course. Their comments were thoughtful, sincere, and extremely helpful. As the authors move into a second offering of the course next year, these observations 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 in improving 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 the authors 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.

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