AC 2010-1951: INSPIRING INNOVATION

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Inspiring Innovation

1. Introduction

This paper describes a course at Syracuse University that brings together architecture and structural engineering students for a joint architecture and engineering design seminar. This course forms part of a larger NSF funded project aimed at increasing innovation and creativity in engineering curricula. The principal aim of the overall project is to find strategies to foster and reward creativity in engineering students. The principal aim of the trans-disciplinary course under discussion here is to investigate the degree to which the integration of architecture and engineering pedagogy is successful in producing desirable outcomes for either group of students. Given their different but potentially complementary skill sets, engineering and architecture students are a natural fit for investigations into creative pedagogy. In fact, the practices of both disciplines are intimately related and, yet, students whose careers may be so closely linked, rarely have opportunities for cross-disciplinary interaction in their formative years, least of all in design contexts where dialogue and collaboration could be so productive for both.

2. Background

Engineering is the discipline of innovation and creativity. But engineering education has lost sight of this central value, one that the pioneers of the discipline (the designers of the great Roman aqueducts, Thomas Telford, the Wright Brothers) so clearly understood. Some of engineering's most recent innovators famously did not finish college (Bill Gates, Steve Jobs, and Michael Dell), in part, because they did not see the relevance of a normative engineering education to their work and their creative technical passions. There is no doubt that both academic and practicing engineers continue to be creative every day in their labs, their jobsites, and their workshops and offices, but engineering education does not consistently address innovation, address its relationship to research and design, or explicitly integrate it into an undergraduate student's training.

On the other hand, creativity in structural engineering design is celebrated in the architectural design curriculum. History courses and design studios study works of recent and contemporary structural engineers such as Peter Rice, Cecil Balmond, Ted Happold, Jorg Schlaich, and Mutsuro Sasaki are well known to architecture students and faculty. These engineers' capacity to integrate technical innovation and aesthetic merit in either their own design projects or collaborations with prominent architects (such as Toyo Ito, Norman Foster, Rem Koolhaas, Zaha Hadid, Kazuyo Sejima, and Renzo Piano) is widely acknowledged. In this Digital Age, architects are continually pushing the limits of design through the use of new technologies and materials, thereby relying on the innovation and expertise of their engineering collaborators.

Although the curricula of both architecture and engineering have required "design" courses, the content and pedagogical goals for these are usually quite different. The traditional "studio" is the core of architectural pedagogy at Syracuse University (as at most schools of architecture). The studio joins faculty with students for 12 hours per week and utilizes a range of pedagogical strategies such as lectures, site visits, one-on-one critiques, group and individual presentations to provide students with the creative and technical skills to address a wide range of design problems. In engineering education at Syracuse University (and in many Civil Engineering programs throughout the country), the design studio is viewed as a capstone course for seniors in the Civil Engineering program and for many students, it is the first exposure to an individual design project. While both the architecture and civil engineering courses emphasize design, they differ in several ways: the architecture studio spends more time on conceptual designs and innovative solutions that do not necessarily bring the projects to a level of technical resolution beyond the schematic; whereas the engineering design course is necessarily focused on the full technical resolution of a normative design problem that typically includes projects from the region i.e., a new highway overpass, a new building under construction on campus, or a water supply system for a nearby suburb.

The pedagogies of the two disciplines are not obviously aligned. A traditional engineering education focuses on technical skill building and on learning to solve specific, bounded, and isolated problems in a series of early courses whereas synthesis of those skills to solve a complex design problem usually comes late in the undergraduate student career. A common engineering teaching paradigm divides complex problems into many pieces which students are then taught to solve independently, all the while anticipating that eventually, they will "be able to develop a solution by combining them" (Katehi 2005). "Eventually," as Ketehi (2005) continues, "the effort involved in learning about the small pieces is so overwhelming that we can longer synthesize the original problem–the parts become more important than the whole." Further, the engineering curricular focus on solving "one problem at a time," assuming a singular answer or solution, stands in direct contrast to "the history of modern technology and society in all its vital messy complexity" (Hughes 1990, 5). As Charles Vest, former President of MIT writes, "There are two frontiers of engineering" and "each is associated with increasing complexity" (Vest 2005). By comparison, the discipline of architecture's curriculum and pedagogy consciously and actively fosters and rewards creativity. Architecture students prioritize innovation and continuously engage in creative thinking while keeping an eye on the big picture: the cultural significance and ultimate aims of the "program" in relationship to the cultural and environmental context of the project. Students are exposed to the best examples of creative endeavor and cutting-edge design practice and taught the history of their field. Throughout their education, students are exposed to a range of approaches and methodologies for problem-solving design, helping to provide the understanding the no one approach is paramount. Architecture students however, often lack the technical skills and expertise of their engineering peers because they take very few hard science, math, or engineering courses. It is usually only through professional experience over many years that architects gain the technical expertise to be able to effectively communicate with their engineering collaborators.

Engineering education researchers and practitioners have widely acknowledged the problem of design education, creativity, and multidisciplinary integration and a number of case studies have helped to inform the Inspiring Innovation project. Previous studies of engineering student design processes report a significant difference between the capacity of student engineers and engineering practitioners in "problem scoping" and "information gathering" at the start of a design project, and argue that engineering students would benefit from teaching methods designed to model that process for them (Atman et al, 2007). In the 1990s first-year design courses were widely introduced in engineering programs in an attempt to introduce students to the nature of their chosen profession earlier in their college careers (Dally, 1994). Dym et al (2005) identify a host of institutions (Harvey Mudd, Purdue, Northwestern, Penn State, Colorado School of the Mines, University of Alabama, Columbia, Cooper Union, Drexel, NJIT, Ohio State, Polytechnic South Carolina, USC, Carnegie Mellon, University of Colorado at Boulder, Georgia Tech) that introduced design thinking through project-based learning in their first year programs. Most of these schools reported a positive impact on retention for those students who had taken some form of first year "cornerstone" engineering design course. Dym et al further argue that such courses have a positive impact on student interest and performance in later engineering courses. A first year design course is likewise taught at SU, where engineering students work in groups under faculty direction to design shopping malls, playgrounds and other projects. At Texas A&M, an integrated engineering science curriculum was developed for the second year whereby more traditional engineering science courses (dynamics, statics, fluid mechanics, thermodynamics etc) were replaced by multi-disciplinary courses where students tackled the analysis of systems that required knowledge of principles from multiple disciplines. An improvement in scores was found on a Fundamentals of Engineering-like test used as a diagnostic, and the new curriculum remained in place (Froyd & Ohland, 2005). Lehigh University has two degree programs, Integrated Design Arts and Integrated Business Engineering, that aim to infuse invention and entrepreneurship into the curriculum through freshman projects, capstone projects and graduate projects (Ochs et al 2001).

3. Course Description

This trans-disciplinary design seminar (TDS) aims to integrate engineering research into the creative design process; it gives students the opportunity to use modeling, software, and algorithms that are generative and performative in the design process, within the context of a faculty-directed research project. This model accommodates creative and research activities such as open-ended problem solving, resolving competing goals in a complex problem, balancing technical merit against architectural design values, and positing speculative designs. For this initiative, 24 students, (11 engineers, 13 architects) come together for a 3 credit hour technical design seminar that is oriented towards a research project that spans civil engineering and architecture and is taught by a structural engineer and an architectural designer. For engineering students, the TDS will also be an opportunity to experience one-on-one instruction typical of design studios, or "desk-critiques" in the architecture vernacular. For architecture students this is an opportunity to work with technical constraints in a new way.

The current incarnation of the TDS is a course entitled "Shell Structures: Speculative Design and Sensational Effects" (future versions may take on different themes in response to faculty expertise and research interests). Curvilinear forms are used in some of the most recognizable works of prominent contemporary artists and architects, such as Anish Kapoor's "Bean" in Millennium Park in Chicago, Sir Norman Foster's Swiss Re Building (aka the "Gherkin"), SANAA's Rolex Learning Center, and much of Frank Gehry's recent work. Although curvilinear form is a contemporary interest and pursuit, the forms are not always optimized for structural performance (such as in some of Frank Gehry's work). This represents a missed opportunity for both architects and engineers since, as every engineer knows, it is the curve that gives the arch and the dome their formidable strength. As far back as the 1920s and 1930s, in fact, engineers have created extraordinary shell buildings where the curved form serves in one elegant move the function of structure, enclosure, and façade. The TDS examines the historical precedents of this form in the work of Antoni Gaudi, Eduardo Torroja, Pier Lugi Nervi, Felix Candela, Heinz Isler and contemporary works by Toyo Ito and Kazuyo Sejima. Precedent analysis is a typical exercise in an architecture design course where faculty present and students research projects that are similar in scale, site or program to the one the students will undertake. It serves effectively to allow students to investigate and identify different strategies for solving design challenges and for integrating and/or prioritizing within multiple design goals. The specific engineers mentioned here will make for particularly good case studies as each was well regarded within both the architecture and engineering community. These designers produced technically innovative and ground breaking shell structures, while also addressing all the other design aspects, in particular, aesthetics. The intention is to learn from these precedents and build upon their expert approach to push the technical and aesthetic possibilities of shell design using contemporary technologies and materials.

There are a multitude of shapes that a shell can use to span a space (with varying degrees of structural efficiency). Students learn about and experiment with "form finding methodologies" rooted in structural performance: the hanging and funicular models of Gaudi and Isler, the straight line-generated hyperbolic paraboloids of Torroja and Candela, and contemporary computer-generated applications. We aim to give the students tools to find these forms and critical skills to evaluate forms for structural performance, as well as teach basic membrane theory for the structural analysis of shells. Students will also analyze their own shell shapes using the finite element modeling programs SAP2000. However, structural performance is not the sole design criterion for the students' work. They will be assigned a real site with cultural context, solar orientation, neighboring buildings, pedestrian and vehicular circulation, that all must be taken into account in the design of the final form. Much like any architectural studio project, a program for the building will be defined, and thus students must consider the size of spaces needed and the activities that will take place in them, how people will move through the building and the site.

A quick note regarding building code is important. Required engineering design classes such as concrete design or capstone design are necessarily concerned with teaching the specific requirements of building code as it pertains to the project at hand. ABET accreditation requirements notwithstanding; exposure to such realities is vital to the training of a professional. Similarly, their accrediting body, the NAAB, requires architecture schools to teach the relevant life safety and accessibility (under the

Americans with Disabilities Act) codes in specific required classes. As an elective course, the TDS will not use building codes as a primary design constraint, however issues such as appropriate loads, strength of materials, conservative safety factors, limits on deflection, life safety, and accessibility will be discussed in the final assignment and in design critiques.

The two groups of students naturally arrive to the TDS with very different skill sets. No one course can or should aim to catch each group up on the years of training the other group has enjoyed. The aim rather is to build enough of a common vocabulary and understanding of each constituency's goals and values in the design process to facilitate collaboration, to inspire each group about the potentials of their own discipline (in the creative AND technical realms), and to foster confidence in future collaborations. In acknowledging this difference in background, the assignments are completed as true collaborations, with the expectation that each member of the group comes with specific and different skills to contribute.

The end result will be an exhibition of the buildings that they design illustrating the many ways in which structurally performative shells can be incorporated into an architectural design while also considering all the goals of the design project. Those goals would include: integration into context, aesthetic appeal, the day-to-day needs of users, and sustainability. We intend to publish this analysis of curved forms, our case studies, and our students' design results in a formal student-faculty authored collaborative essay.

4. Course Outline

At the time of writing, teaching of the course is half complete. The first half of the course focused on introducing shell (forms and their structural and architectural performance), skill building (physical modeling, membrane theory, form generation in Rhino and CADenary, and finite element analysis in SAP2000), and establishing a common vocabulary for the architecture and engineering students. The second half of the course will build on the projects of the first half (see below) but will concentrate on one longer final design project. All of the assignments are undertaken in pairs/groups with a mix of engineers and architects.

Week 1:	Wed:	*Lecture*: Introduction to Shells and Diagnostic Surveys.
Week 2:	Mon:	*Lecture*: What is a Shell? – Engineering Definitions and Inspirational Examples. *Reading Discussion #1:* Salvadori, Mario. "Form-Resistant Structures," in Why Buildings Stand Up. W.W. Norton & Co.: New York, 2002
	Wed:	*Lecture*: Shells, Curvilinear Form and their use in Contemporary Architecture. *Assignment #1:* Paper Parabolas.
Week 3:	Mon:	*Working Session:* Students only, instructors at NSF awardees

Conference.
Wed: *Pin-Up:* Paper Parabolas.

Week 4: Mon: *Lab:* CADenary, hanging/centenary form finding software.
Focus Groups: Group Interviews with Education Evaluation Team.
Wed: *Lecture:* Antoni Gaudí, Heinz Isler and the Hanging Form.
Assignment #2: Frozen Form.

Week 5: Mon: *Lecture:* The Mathematics of Shells – Introduction to Membrane Theory.
Reading Discussion #2: Burry, Mark. "Virtually Gaudi" Digital Tectonics. Neil Leach, David Turnbull, Chris Williams. Wiley-Academy: Great Britain, 2004.
Wed: *Pin-Up*: Frozen Form.

Week 6: Mon: *Lab:* Introduction to form generation in Rhino (3D modeling software).
Wed: *Lab:* Curvilinear form in Rhino.

Week 7: Mon: *Lecture:* Dynamic Experience: The architectural nature of interior and exterior space created by shells.
Wed: *Lab:* Introduction to Finite Element Analysis of Shells using SAP2000

Week 8: Mon: *Lecture*: Aperture and Aggregation – The use of modular design in shell structures.
Reading Discussion #3: Bechthold, Martin. "Form and Structure" Innovative Surface Structures. Taylor & Francis: New York, 2008.
Assignment #3: Aperture and Aggregation.
Wed: *Pin-Up*: Part 1 of Aperture and Aggregation – Module Studies

SPRING BREAK

Week 9: Mon: *Lecture:* Felix Candela and the Hypar – Modules, Aggregation, Aperture and Performance.
Wed: *Lab:* Introduction to CNC Milling and Vacuum Forming

Week 10: Mon: *Lab:* Desk critiques and technical instruction on design projects
Wed: *Pin-Up:* Part 2 of Aperture and Aggregation – Final Models

Week 11: Mon: *Lecture:* Introduction to Final Project and Precedent Analysis
Assignment #4: Precedent and Site Analysis
Wed: *Site Visit:* Site Analysis

Week 12:	Mon:	*Pin-Up:* Precedent and Site Analysis
	Wed:	*Desk Crits/Working Session:* Schematic Design
Week 13:	Mon:	*Lab*: SAP testing of Schematic Design
	Wed:	*Pin-Up*: Schematic Design
Week 14:	Mon:	*Desk Crits/Working Session:* Final Design and Model Making
	Wed:	*Desk Crits/Working Session:* Final Design and Model Making
	TBA:	*Focus Groups* Group Interviews with Education Evaluation Team.
Week 15:	Mon:	*Final Project Review*
	TBA:	*Final Diagnostic Surveys*

5. Course Goals

Through teaching and evaluation of three iterations of this course we hope to:
- establish a permanent cross professional course at Syracuse University;
- provide a model for similar collaborations between engineering departments and other "creative" disciplines at SU;
- learn about students cross professional perceptions and their perceptions of their own skills;
- study the effect (if any) that trans-disciplinary activities can have on those perceptions;
- find teaching methods that allow engineering students to develop skill and confidence in integrating their technical knowledge into more broadly conceived design endeavors.
- find teaching methods that allow engineering architecture to develop skill and confidence in collaborating with technical experts on their design endeavors.

We hope that the content and teaching methodologies will foster learning and growth for both engineering and architecture students. Creativity will be encouraged through multiple outlets that promote research, design and problem solving for open-ended, value-driven guidelines and aesthetic goals. Through this course, engineering and architecture students will learn the value in collaborating to work towards aesthetic and technical goals to produce beautiful, efficient structures. Group discussion of the design projects will help to foster the understanding amongst all students that a multiplicity of approaches exist and that the success of the proposals can be assessed using (equally important) aesthetic and technical criteria.

Through these collaborative projects, students will develop and harness their confidence when approaching open-ended challenges. Working in interdisciplinary design partnerships will be crucial to the success of the project, and therefore, we hope students will develop a greater appreciation of their own as well as the other discipline. Learning how to communicate with one another will be an important process throughout the semester, which will also affect students' attitudes about the disciplines. The differences in vocabulary will be discussed openly in the classroom to create an environment of mutual respect and support.

6. Course Evaluation

In order to study the degree to which these goals are met by the course an evaluation plan has been prepared by the Office of Professional Research and Development in the School of Education at Syracuse University. Students were evaluated at the outset, will be further evaluated at end of the course for issues that range from their expectations of the course, their assessment of course content, to their sense of their own performance as well as more traditional measures of the course and its instruction. These evaluations will be used to assess whether the course is achieving its objectives and to make necessary adjustments to it.

For the purpose of evaluating the TDS course, we ran a student survey at the beginning of the semester (pre intervention). This survey was administered to all students. The respondents were anonymous, but distinguished in terms of discipline and gender. The survey responses complement the information gained from the diagnostic test. In addition to the survey, the evaluation team conducted focus groups, in order to get more depth on some of the questions from the survey. Both survey and interviews include questions on student expectation and current perceptions within the following areas: Creative Problem Solving, knowledge acquisition, and cross profession perceptions. Questions will pertain to: confidence in approaching problems; ability to see problems from multiple vantage points; fluency, flexibility, originality, elaboration ability; conceptual intuition; actual achievement in discipline content; self perceptions of knowledge; productive group leadership; perceived satisfaction; product originality and utility; attitudes of engineering and architecture students toward each other and their professions; inspiration and motivation to continue in engineering; perceptions of cross-discipline utility.

7. Initial Findings

When first announced in the fall the course proved immediately popular with both groups of students. All 12 engineering slots were filled within 24 hours of distribution of the flyer, the architecture slots were filled similarly quickly and a long waiting list developed. At the time of writing teaching of the course is half complete and the initial round of evaluation (surveys and focus groups) is complete.

In the class, the collaborations between engineering and architecture students are working well, but the lack of a shared vocabulary and the importance of clear definitions of terms have emerged as significant. Often it is a matter of pushing both groups to fully explore what they understand by a given term to see that there is common ground. For example the term "differentiation": an architecture student or faculty member might use "differentiated" to describe the physical articulation of surface or a volume. To the engineering student this is initially impenetrable, but when pushed to fully recall the definition of dy/dx as relating to change of a given parameter with respect to another (perhaps thickness or height with respect to location) the architect's use of the word becomes more clear. By contrast, engineering students were less thrown by the introduction of Rhino 3D modeling software (that most of the architecture students are already somewhat familiar with) than we had expected. They could see clear parallels with AutoCad and found that most shapes are constructed using commands that use the parameters of the shape's mathematical equation. Some of the architecture students had been using the software in a less precise way and have been enthusiastic to investigate the degree of control that these commands have when you fully understand the mathematics behind them.

Engineering students initially expressed frustration with the open-ended assignments. But considering they arrived at one of the first classes comparing notes on the assignment from the class they just left, establishing that "everyone got beta equals 0.6" and so life was good, they have proved remarkably flexible. With each successive assignment the "engineering partner" has begun to flex his or her technical muscles while at the same time demonstrating a desire to embrace aesthetic goals. They have begun to be more confident in finding an entry point into an unfamiliar problem and a more willing to take a risk and try something when they are unsure.

When asked a series of questions about their perceptions of themselves and their discipline in the initial diagnostic survey some intriguing initial results emerged. Engineering students on average rated themselves as more creative and artistic than they (or the architecture students) rated engineering students as a whole. By contrast they rated themselves on average as less intelligent or logical than the average engineer. These results are somewhat surprising and require comparison with a control group of engineers to see if there is a larger trend or if we have a self-selected group. There is a clear difference in the self-perceptions of architecture and engineering students with the architecture students having more confidence in their own skills in almost every arena than the engineers had in theirs. There is no evidence in the respective GPA's or class standing to explain such a difference.

8. Conclusion

In conclusion, this experimental new course aims to merge the pedagogical paradigms of engineering and architecture to foster and reward creativity in engineering students and to investigate the degree to which the two disciplines are compatible in the academic environment. Evaluation and refinement of the course will aim to find teaching methods that successfully inculcate creativity and innovation in engineering design. It is intended to use the evolution of this course and the results of the evaluation plan over successive years to develop a model for trans-disciplinary design courses at SU and beyond.

Acknowledgements

This work was carried out with the support of NSF 08-610- Innovations in Engineering Education, Curriculum, and Infrastructure (IEECI) Award EEC-0935168, and the support of the Syracuse University School of Architecture and the L. C. Smith College of Engineering and Computer Science at Syracuse University.

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