
AC 2012-3765: STRUCTURAL ENGINEERING FOR ARCHITECTURE AND CONSTRUCTION MANAGEMENT STUDENTS: TEACHING METHODS AND CHANGING NEEDS

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Structural Engineering for Architecture and Construction Management Students – Teaching Methods & Changing Needs

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

The ARCE department offers a sequence of five support courses that are taken by architecture and construction management students and gives them a solid grounding in statics, properties of materials and structural systems. The final two courses in this sequence are titled *Small Scale Structures* and *Large Scale Structures*. These two courses are unusual in that they are designed not for ARCE students but solely for the ARCH and CM students.

In presenting these two culminating courses, this paper addresses the background of the support course sequence, the role these two courses play in the five course sequence and their goals, learning outcomes, content and methodologies and approaches. This paper will also describe the interdepartmental assessment processes and how these two unusual courses show successful strategies for providing cross-discipline education.

Background and the Five Course Sequence. The curriculums for the ARCH and CM students at Cal Poly have, for many years, included structural engineering courses taught by the ARCE department. In 2005 the ARCE department updated the sequence of courses required for the ARCH and CM students. The earlier six course sequence, which included three structural material specific design courses, was replaced by a five course sequence in which the three material design courses were replaced with two courses focused on small scale and large scale structures.

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

- *Structures I (3 units with 2 hours of lecture and two hours of activities per week)*

- *Structures II (3 units with 2 hours of lecture and two hours of activities per week)*
- *Structural Systems (3 units with 3 hours of lecture per week)*
- *Small Scale Structures (4 units with 4 hours of lecture per week)*
- *Large Scale Structures (4 units with 4 hours of lecture per week)*

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

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

Following the *Structural Systems* course, the ARCH and CM students take a *Small Scale Structures* and then a *Large Scale Structures* course. While the *Structural Systems* course is material neutral, the *Small Scale Structures* and *Large Scale Structures* courses are material specific. The *Small Scale Structures* course focuses on timber and single story steel framed buildings. The *Large Scale Structures* course focuses on multi-story reinforced concrete and structural steel framed buildings. Students learn the characteristics, advantages and disadvantages of different structural systems, how to evaluate the different systems and how to develop the preliminary structural designs of buildings. The courses also cover foundations, cladding and long span and high rise structures.

The primary goal of this series is to give these students tools that will assist them in their careers as project leaders so they can better produce efficient integrated designs and collaborate effectively with their structural engineering consultants and therefore lead more successful projects.

The benefits of understanding structural principles apply to both ARCH and CM students. Architects typically take a lead role in building design and so an understanding of structural principles can enhance their ability to produce design concepts that are coordinated with an efficient, well thought out structural system. Understanding structural concepts and nomenclature allows the architect to more effectively communicate with their structural consultants and better develop the structural system. In addition, the architect, as team leader, often has the direct communication with the client or owner and a better understanding of structural principles allows them to better communicate structural principles and the implications

of structural decisions to the owner. The decisions of an informed owner are more likely to result in a successful project. An understanding of structural engineering principles acquired as an architecture student can therefore be of great benefit in his or her career.

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

An additional benefit of these courses to students is that they encourage interdisciplinary collaboration. This occurs between the ARCH and CM students in the classroom and also with the ARCE faculty. Although informal, it is not uncommon for ARCH and CM students to consult with their ARCE faculty regarding structural systems for their studio projects.

Learning Outcomes & Outlines. The learning outcomes of the two culminating courses, *Small Scale Structures* and *Large Scale Structures*, are based on the overall goal of giving the ARCH and CM students the structural engineering skills and the understanding of structural engineering principles that will serve them in their careers as project leaders. These courses, structural engineering for architectural and construction management students, are very unusual with little published material on the subject. The engineering education literature includes discussions of a number of interdisciplinary courses. Some of these interdisciplinary courses include engineering students from multiple disciplines^{1,2} or engineering students and business or marketing students^{3,4} and some interdisciplinary courses are focused on the design and construction disciplines and include architecture and construction management students as well as engineering students^{5,6,7}. However the literature on these courses is of limited relevance and provides limited guidance. Although the courses described in this paper courses have an interdisciplinary component, they are not really interdisciplinary. They teach structural engineering skills and principals to non-engineering (architecture and construction management) students but do not contain the content of multiple disciplines and do not function as interdisciplinary courses.

One paper describes the different curriculum approaches typically employed for architectural and engineering programs⁸. The paper describes how engineering programs work from the “ground up” starting at a very detailed level and gradually advancing to systems only at the end of a program, while architectural programs typically use a studio approach which introduces students to the design of full projects at an early stage. Courses involving architecture students with engineering content should ideally recognize these two approaches.

The learning outcomes of the two culminating courses described in this paper have been defined to include content with an appropriate level of structural engineering rigor and accommodate the architectural and construction management disciplines, by including a balance of architectural design and construction issues. The learning outcomes also provide a balance of detailed engineering skills and big picture design considerations. The learning outcomes have been repeated below:

Small Scale Structures – Learning Outcomes

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

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

Large Scale Structures – Learning Outcomes

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

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

Although the learning outcomes are somewhat general, the outlines for these two courses include a significant amount of structural content. The structural content in the course outlines includes: the development of vertical and lateral loads, gravity and lateral configuration issues, gravity and lateral structural systems, rigid and flexible diaphragm behavior, timber, steel and concrete material properties, the design of timber, steel and concrete gravity systems, an understanding of timber, steel and concrete lateral systems, structural material finishes and connections, tall buildings, long span structures, cladding and deep and shallow foundation systems.

These course learning outcomes and outlines reflect a rigorous architectural engineering approach that the ARCE faculty believes is appropriate for the course. However the classes have typically also included content and approaches intended to both inspire the ARCH and CM students and provide skills specific to their future careers. This is reflected in the methodologies used by individual instructors.

Methodologies. Several types of classroom methodologies have been used by instructors. All have been successful in meeting the learning outcomes and covering outline topics. However each has done so in different ways reflecting instructor's backgrounds and providing a diversity of student experiences. These methodologies include graphic analysis, computer modeling, physical model building and individual and team projects. The types of class materials varied

with the type of activity used in the classroom. In general, textbooks were not used and each instructor used materials developed from his or her experience. The different methodologies are described below.

Graphical Analysis methods for the design of curvilinear and long span structures was one approach used for the *Large Scale Structures* course. The graphical method used is a venerable part of structural engineering tradition, beginning with Karl Culmann's *Die graphische Statik* from 1864. It has more recently been championed by Allen and Zalewski in their 2010 book *Form and Forces*. The use of graphical statics in a modern engineering course readily allows students to see how structural form and structural forces are inescapably intertwined. This is a rigorous, yet visual approach to the design and analysis of these special structures that worked well with both the architectural and the construction management students. A representative assignment was the design, using graphical statics, of a 110 foot span, cable supported footbridge. Figure No. 1 shows a sample student submittal. The analysis and design was performed by all students, with three dimensional renderings executed by the ARCH students and construction sequences described by the CM students.

This approach provided a visual and somewhat intuitive approach to the preliminary design of special structures that these students will employ in their careers. It is also especially appropriate for the curvilinear structures that may not lend themselves to simple manual calculations. The approach of assigning different tasks to the architectural and construction management students recognized their strengths and encouraged interdisciplinary collaboration.

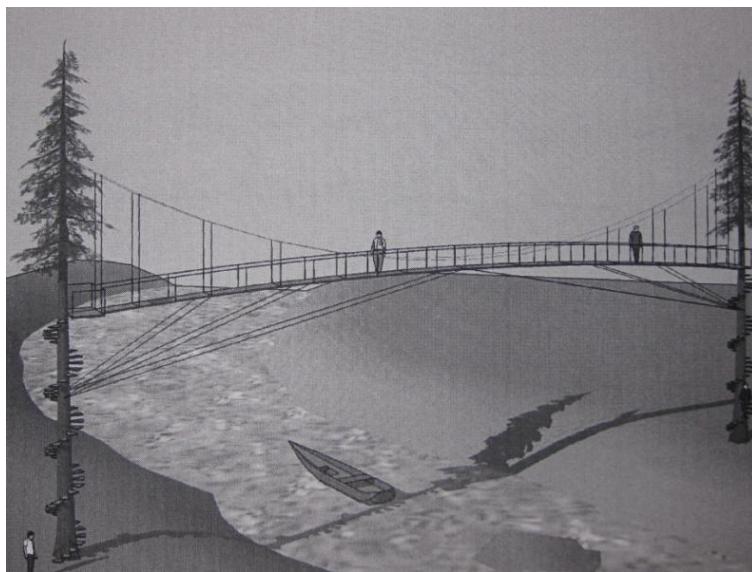


Figure No. 1 - Graphical Analysis Assignment (image by Ed Saliklis)

Computer Analysis was one methodology used for the tall buildings module of the *Large Scale Structures* course. The tall building module included a review of the history and development of tall building structural systems as well as a review of the behavior of the structural systems now in use. A review of the structural trends in tall building construction over the last 130 years from masonry to moment frames, braced frames, tube and outrigger systems as well as a contextual description of the engineers who developed these designs provides an appropriate level of

structural literacy appropriate for future project leaders. Such a historical review, tracing the actual engineering ideas created by key engineers is another means of making the principles of structural behavior come alive to the students. After visual presentations of the fundamental principles of tall building behavior, students prepared elementary computer models of buildings with outrigger systems as well as models of buildings using dual braced frame-moment frame systems. The intent of this approach was not for the students to acquire computer analysis skills, but for them to understand, from their own work, structural principles such as the different deformation patterns of braced frames and moment frames and the load sharing benefits of outriggers in tall buildings. A useful feature of the computer models is the ability to exaggerate the deformations, thus driving home what might be an otherwise too subtle distinction between, for example, shear behavior and cantilever behavior.

Physical Models have been used in the *Structural Systems*, the *Small Scale Structures* and the *Large Scale Structures* courses.

In the *Structural Systems* course, models have been used to demonstrate principles of stability and configuration for structures composed of axial as well as flexural members.



Figure No. 2 - Structural Systems Course Models (photos by the author)

In the long span module of the *Large Scale Structures* course, students worked in groups of three or four to design and construct one-way long span models using wood applicator sticks and dowels. The objective was to have the students understand the requirements in making closed section trusses and to explore the resulting possibilities.



Figure No. 3 - Large Scale Structures Models (photos by Jake Feldman)

In a later assignment on space frames, students were introduced to the variety of geometric patterns that can be employed along with the support options that result in stable structural configurations. The students then designed and built models of a large covered space and

experienced the visual and construction complexities resulting from choosing a space frame systems. Examples of student submittals are shown in Figure Numbers 2, 3 and 4.

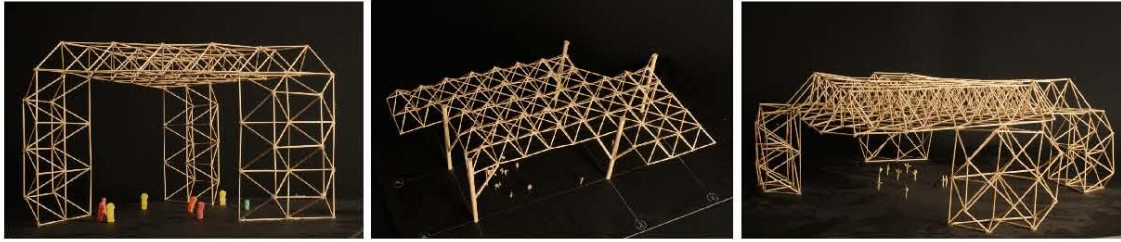


Figure No. 4 - Large Scale Structures Models (photos by Jake Feldman)

Students also used physical models in a study of domes. A variety of geometries related to single layer domes were introduced along with the concerns for overall configuration stability. The models demonstrated the structural efficiency of domed geometries along with the visual nature of the spaces created.

Students also created scale models of reinforced concrete. The possibility of students being able to take coursework that includes the construction of scale model buildings out of reinforced concrete is an educational opportunity unique to Cal Poly. Over a period of several weeks student teams designed and constructed reinforced concrete buildings in a 48 foot long sand-filled casting table. This activity has many educational benefits:

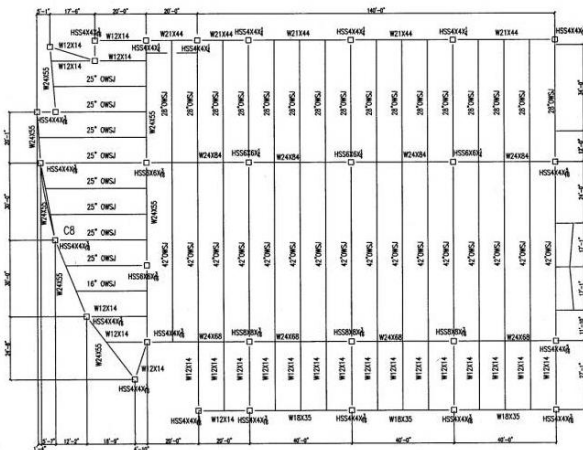
1. The students dealt with the possibilities and problems inherent in the use of reinforced concrete from the design through the construction phases.
2. The ability to design in concrete required an understanding of construction sequencing and continuity. By going through the process, the students were better prepared to understand how to “think in concrete”.
3. The students learned that concrete can be both the skin and the skeleton of the building.
4. The course very graphically introduced the students to the nature and necessity of foundations.
5. The students learned, at a small scale, the purpose and placement of reinforcing.
6. The students experienced the structural demands on formwork along with the difficulty of fabricating formwork, the nature of placing and finishing concrete, the anxiety and anticipation of removing formwork and the satisfaction and thrill of a successful pour.
7. Students began to learn the design tension between structural order and design freedom.

These are lessons that will stay with students throughout their careers. Samples of the students’ work are shown in the photos in Figure No. 5.



Figure No. 5 - Large Scale Structures Concrete Models (photos by Jake Feldman)

Projects, both team and individual, have been used in both the *Small Scale Structures* and the *Large Scale Structures* courses. The students produced preliminary structural designs for the types of building that they are likely to encounter in their careers. In the *Small Scale Structures* course these included a single-story school building, a middle school auditorium and a community college library.



Roof Framing Plan



Figure No. 6 - Small Scale Structures – Representative Project (photo by the author)

For the *Large Scale Structures* course, projects included a four-story, two building computer center and a four story public library. The projects were all based on actual buildings.

The students were given preliminary floor plans from which they prepared column and lateral system layouts. They then prepared preliminary structural designs for the gravity and lateral systems for the different structural materials presented in the course. In the *Small Scale Structures* course, alternate preliminary designs were prepared for structural steel and timber systems. In the *Large Scale Structures* course, alternate preliminary designs were prepared for structural steel and reinforced concrete systems. The preparation of the preliminary member designs used simplified design methods and rules-of-thumb.

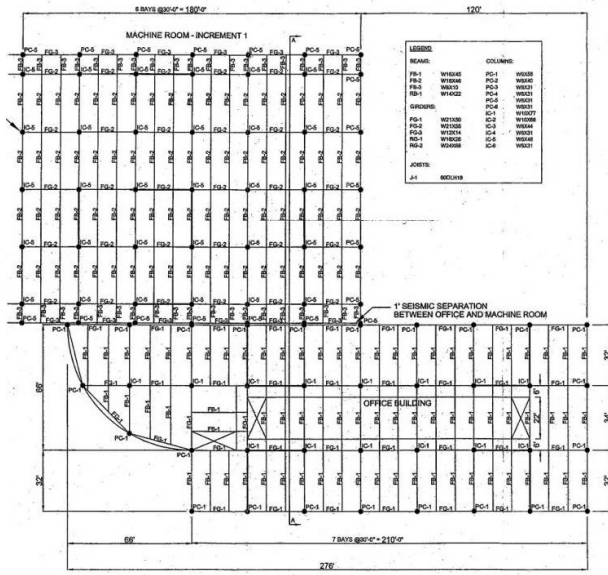


Figure No. 7 - Large Scale Structures – Representative Project (photo by the author)

At the end of the quarter, students compared the alternate systems, developed systems recommendations and presented their conclusions to the class.

This project approach reinforced lectures on structural configuration, preliminary framing design and the evaluation of alternate structural systems. It gave the students a connection between the classroom work and actual building projects, an introduction to the comparison and selection of alternate structural systems and a feeling for structural framing sizes that should serve them well in the future. Sample framing plans and photos of the buildings on which the projects were based are shown. Figure No. 6 shows a photo of the community college library that was the basis of one of the projects and a sample framing plan submitted by one of the students for the Small Scale Structure course. Figure No. 7 shows a sample framing plan submitted by one of the students and a photo of the computer center that was the basis of one of the projects for the Large Scale Structure course.

Assessment. A formal assessment of the relative effectiveness of these different methodologies, graphic analysis, computer modeling, physical model building and individual and team projects, has not yet been undertaken. However observations can be made from the perspectives of student assessments in subsequent courses and comments by ARCH and CM faculty and students.,

Subsequent Student Assessments. Course evaluations by architecture and construction management students for another, senior level course, appear to demonstrate the overall effectiveness of the five course sequence. Three years ago the college introduced a new capstone interdisciplinary course in the form of a project based, team oriented, studio laboratory. The course requires small teams of architecture, architectural engineering, construction management and landscape architecture students to complete the schematic level design of an actual building for a real client.

Student course evaluations have now been collected for seven quarters. Students are asked to assess their knowledge of disciplines other than their major prior to and after the interdisciplinary course on a scale of 1 to 5, with a score of 1 being little or no understanding, a score of 3 being a basic understanding and a score of 5 being a thorough understanding. The data is summarized in Figure 8.

Interdisciplinary Course Student Course Evaluation Summary						
	Prior to Course	After Course	Average Change	Prior to Course	After Course	Average Change
Discipline	ARCE Students			ARCH Students		
ARCE	--	--	--	3.0	3.9	+0.9
ARCH	2.4	3.5	+1.1	--	--	--
CM	2.6	3.7	+1.1	2.5	3.3	+0.8
LA	1.4	3.0	+1.5	2.9	3.8	+0.9
	LA Students			CM Students		
ARCE	1.4	2.8	+1.4	2.5	3.3	+0.8
ARCH	2.3	3.7	+1.4	2.0	3.4	+1.4
CM	2.4	3.9	+1.5	--	--	--
LA	--	--	--	1.7	3.2	+1.5

Figure No. 8 Assessment of Non-Major Discipline Knowledge

In addition to showing an improvement in knowledge of other disciplines, a learning outcome of the interdisciplinary course, the data shows the level of understanding for each of the other disciplines that students entered the course with. There is a significant variation between the different department's students that reflects the different curriculums of the four disciplines. ARCE students take three lower division architectural studio courses as well as several construction management courses and of course ARCH and CM students take the ARCE five course structural engineering sequence described in this paper. The survey results indicate that ARCH and CM students' knowledge of ARCE prior to the course was higher than that of any other non-major discipline. The entering scores were 3.0 for ARCH students and 2.5 for CM students. A score of 3.0 is associated with the course evaluation statement of: "I have a basic understanding and I am comfortable with its needs on a project". On this basis, the five course sequence appears to be have been successful.

Interdepartmental Assessment. An assessment of the five course sequence and especially the two culminating courses is now underway. The assessment includes reviews by the ARCE faculty and meetings with ARCH and CM faculty. The ARCH and CM faculty stated that they recognized the value of the ARCE five course sequence and reported a variety of recommendations and comments from their students. The ARCH students liked the physical models and enjoyed the presentation of famous building studies. They also liked the emphasis on the design aspects and the holistic discussion of load path, bracing layout and an understanding of how structures work.

The CM students liked the interdisciplinary aspect and wanted to understand the cost, schedule and constructability aspects of different structural systems. They were interested in the integration of systems such as superstructure, foundations, cladding, etc. The courses sometimes contained significant calculation content and although they may object to being treated like ARCE students, they said they don't mind the rigor and calculations when they can see the benefit.

Both the ARCH and the CM departments reported inconsistencies amongst instructors. Given the range of methodologies, this was not surprising to hear. However we believe there is value in this variety.

The comments reported above will likely result in evolutionary changes in the courses. In addition a recent request by the ARCH faculty may result in more significant changes. There was an observation by ARCH department representatives that their upper division studio projects often include insufficient consideration of building structure and the ARCH department has requested that the ARCE department consider ways to include ARCE faculty and content in the ARCH studios. Several possible methods have been discussed: co-teaching, structural learning modules, coach/consultant and companion courses. ARCE faculty has expressed a preference for 2 unit companion courses to selected studios. With this model, an ARCE faculty member would not just act as a coach/consultant to students, but would provide lectures tailored to the studio project and would assess the students on their implementation of structural concepts as well as providing consultation to the students. The CM department has also expressed an interest in this approach for their laboratory courses. An implication of this change is that a restructuring or consolidation of the *Small Scale Structure* and *Large Scale Structures* courses would be required to avoid adding units to the five course sequence. These of course would be significant modifications of the five course sequence and discussions between the three departments to implement them are continuing.

Conclusion. We believe this five course sequence of support courses provides the college's ARCH and CM students an understanding of structural principles and systems that will serve them well in their future careers. This understanding of structures will allow them to produce design concepts that are coordinated with efficient well thought-out structural systems and it will enhance their ability to make decisions that have structural implications, encourage better collaboration with their structural consultants and allow them to better communicate structural issues to the owner.

The department learning outcomes and content for these courses include the acquisition of basic structural knowledge and preliminary design skills. These may be met in a variety of ways and the instructors teaching the final two courses have exercised significant freedom in the methodologies employed in their classrooms. These methodologies have included graphic analysis, computer modeling, physical model building and individual and team projects with sometimes more than one approach used in a class. This variety of approaches provides those teaching the courses with a wealth of approaches to use in the classroom and may also provide other institutions with examples they may incorporate into their programs.

The ARCE Department, with the Architecture and Construction Management departments, is now reviewing the five support course sequence and especially the two culminating courses. Several changes are being considered. One is to further define and reinforce learning outcomes

and content but also to allow diversity in instructor methodologies and approach so instructors can teach to their strengths and incorporate approaches that best engage the students. The other is a pilot program that would provide ARCE faculty assistance to ARCH studios and perhaps CM laboratories and a consequent re-structuring of the *Small Scale Structure* and *Large Scale Structures* courses.

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