Innovations in Teaching Upper Level Structural Design:
The Italian Experience from the 2nd Century to 1979

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Abstract

Upper level students with a structural analysis and design emphasis in architectural engineering programs are anxious to try their hands at the design of large, complex structures, especially large span shells and domes. However, while most of these students are well founded in the basics of structural analysis and design, many have not been exposed to the trials and innovations of engineers and architects who have dealt with these issues throughout history. In addition, few students have been exposed to intuitive methods of structural design. This paper reports on a short course-within-a-course developed to fill this void in architectural engineering curricula.

Background

The architectural engineering program at the University of Kansas is a five-year, ABET-accredited curriculum which is jointly administered by the School of Engineering and by the School of Architecture and Urban Design. Graduation from architectural engineering requires the completion of 164 credit hours of courses which, in the last three years of study, are taught mostly by faculty from either the School of Engineering or from the School of Architecture and Urban Design.

Architectural engineering students are exposed to a broad range of topics including architectural design, building technology, structural analysis and design, mechanical and electrical equipment, illumination and construction management. As part of the humanities and social sciences requirements of the curriculum, students also complete a three course sequence in architectural history. However, this three course sequence is taught with an architectural design emphasis rather than an emphasis on the technological or engineering aspects of the buildings studied.

The basic philosophy of the architectural engineering curriculum at the University of Kansas is to expose students to the wide range of engineering and architectural subjects involved in the design and construction of buildings. While students do have a series of elective courses available in each of the above areas, which allow them to develop an “area of emphasis”, students do not “major” in any single area. However, graduating seniors are required to complete their education with a capstone course taken during their last semester in school which does allow them to design complete building systems in their chosen area of emphasis.

The capstone course for students with an emphasis in structural analysis and design is ARCE 681 - Architectural Engineering Design II, Structural Section. Since this will be the last course these students take before entering their professional internship, it was decided to allow them to utilize their engineering education and tackle a semester-long problem that would not only reinforce the engineering
principles—already—studied, but would also expand on that education and expose the students to topics normally introduced at the graduate level.

At the beginning of the course, students were presented with a syllabus outlining the course requirements and setting a series of oral and written progress reports established to monitor the development of the students throughout the semester. The project assigned was the analysis and design, both architectural and structural, of a high volume, large span structure of the student’s choice. Projects included sports arenas, transportation terminals and museum/exhibition halls. Students were told that the object of the course was to develop an understanding of the particular problems associated with large structures and to reinforce the concept that structural systems can, in themselves, establish the architectural and esthetic design of a building.

At the beginning of the semester, a series of lectures was presented giving the students techniques to use in the preliminary design of structural systems required for this course. These techniques emphasized the necessity for understanding the structural behavior in large systems and attempted to enhance the students intuitive feelings for the interaction between structural elements. It was emphasized that these techniques should be used during the preliminary design phase of the course.

While these preliminary design techniques were being discussed, it became evident that the students were interested in this type of problem, but they had only a rudimentary knowledge of the historical aspects of the design of large span, high volume structures where the structural system actually became the architectural statement for the building. All of the students had completed the required three-course sequence in architectural history, but those courses concentrated on the architectural philosophy and design of the individual structures. Consequently, it was decided to develop a series of lectures to be given during the semester that would provide some historical insight into projects of this type. Since the instructor for the course had spent considerable time in Italy over the previous fifteen years, Italian structures were chosen as the topics for these lectures.

The Lecture Series

The mini-course was structured as a series of lectures to be presented during the first part of class time. The lecture outlines were developed to present one building during each lecture; however, a number of the smaller building lectures were combined into single lectures, which reduced the overall number of lectures in the sequence. The particular buildings chosen for this sequence each had a significant role in the development of the overall thesis. While other buildings could have been included, the ones presented here seemed to work well as a package.

The evolution of structural theory and design can be traced through many cultures. By 1500 BC the Mycenean culture had developed the corbel as a means of spanning openings over doors and/or windows. By 700 BC the Greeks were regularly using post and beam construction in stone, and they had developed a method of using molten iron to fasten building elements together. However, during the following 700 years, the world experienced the rise of the Roman Empire and, with it, the development of capabilities to span large distances. The Roman arch is well known as a means of supporting buildings, roads and other engineering structures. In addition, during this same time frame, the Remans developed and began using a form of cement, which, when mixed with aggregate, became a form of concrete that could be used in building construction. With this innovation, the Pantheon was constructed during the 2nd century AD. Not only was the Pantheon the largest building constructed to that time, it is now the only building remaining and in use from ancient Rome. This building became the first to be included in the lecture sequence for graduating seniors with a structural emphasis. Of particular interest were the construction techniques used during the initial construction of the dome and the manner the outward
As construction continued in Italy, technology and structural innovation also continued. With the renaissance throughout Europe came the construction of numerous cathedrals and in particular the Duomo of Florence. Begun in 1296 AD, the cathedral was designed, and construction was supervised by Amalio Cambio. Unfortunately, Cambio provided an octagon foundation for the dome, while all existing domes were circular in shape, and he had absolutely no idea how to design or construct the dome on that foundation. The solution to this problem is one of the most innovative structural solutions in history, and the design and construction of the Florence Duomo, begun in 1420 AD, and the politics of that solution were the subjects of lecture number two.

In the early 1930s a group of innovative engineers and architects began a movement to modernize industrial architectural design in Italy. Taking their inspiration from the architectural heritage of the Roman Empire and recognizing the design possibilities of reinforced concrete, these architects and engineers led the world in the innovative use of this material. Through public and private buildings of all types, these professionals created a new architecture that formed the foundation for modern architecture throughout the world. Foremost among this group is Pier Luigi Nervi (1891-1979), who trained as an engineer and practiced as an engineer/architect. His innovative use of concrete as a building material and his intuitive feel for the distribution of stress in his structural shapes established a standard of design that remains today. The buildings of Nervi, the thought process of his engineering, and the way that engineering progressed and integrated with his architectural design throughout his career were the subjects of the remaining lectures in this series.

The first facility discussed in the final series of lectures was the Municipal Stadium in Florence, built in 1929-1932. This is actually the first major project Nervi designed, and he won the commission through a competition. Of particular interest is the resolution of the internal forces in the stadium canopy by the configuration of the structural elements and the design of the exterior stairs, which are helicoidal spirals. Mathematical methods to predict accurately the stresses in these double helix, exterior stairs were not available at the time, so Nervi reduced the system to statically determinate elements and increased the allowable stress in the materials. Tests on the completed system indicated that this approach was amazingly accurate.

The remaining lectures emphasized only buildings designed by Nervi, but they were chosen to illustrate especially the growth of Nervi’s expertise as a designer and innovator of concrete structures. By following the progression of these structures, it is easy to see how this architect/engineer grew and progressed throughout his career.

Of immediate interest is the design of a series of airplane hangars for the Italian Air Force. A competition was held in 1935 for the design of a series of aircraft hangars to be 330 ft. by 135 ft. with 165 ft. door openings. Nervi was awarded this contract based upon the economy of his design. He chose a geodetic framework for these units with a tile roof over a lamella vault. While this design proved exceptionally strong, the value of studying these hangars is in the changes that were made in the design between hangars no. 1 and 2. Construction of hangar no. 1 required extensive form work and welding of the reinforcing steel. With hangar no. 2 the roof members were prefabricated on the ground, lifted into place and then welded together. This system of prefabrication also produced exceptionally strong units. However, of importance in this study, the prefabrication allowed hangar no. 2 to be constructed at a cost substantially lower than the cost of hangar no. 1.

The remaining lectures in this series also were chosen to demonstrate a particular principle in the design of long span, high volume structures. For example, the design and construction of the Exposition Hall (Salone “B”) in Milan continued and improved Nervi’s use of prefabrication and also introduced
"ferro-cemento" which allowed very thin members to span large distances. The salt warehouse in Tortona used parabolic arches with prefabricated lattice ribs between, while the G. A.T.T.I. wool factory in Rome used stiffening ribs cast in each bay to follow the isostatic lines of the principal moments in the floor slabs. The remaining lectures were chosen to demonstrate similar innovations combined with excellence in architectural design.

**Project Evaluation**

There is no doubt that the students in the class described here understand the considerations necessary to design long span, high volume structures better than previous groups who have taken the class. They now have an appreciation of how innovative structural and construction systems can not only improve the engineering of these buildings, but can also provide an interesting and well-designed architectural statement for the building as well.

When the class began and the students were presented with the class project, many were anxious to begin and actually completed proposals as to how they would meet the requirements of the class. They particularly liked the fact that they could choose a structure of their choice and were not being told what kind of a facility to design. However, the beginning sketches prepared by these students generally lacked vision of how innovative structural systems could define the architectural statement of the final design. In general, most of the preliminary designs presented followed the time tested strategy of providing a structural system to “hold the building up” and then covering up that system with other cladding materials.

As the lectures commenced, it was noticed early that a number of the students appeared to be viewing their projects with a more critical eye. Following the lectures on the Pantheon and the Duomo in Florence, these students re-evaluated their designs and attempted to resolve the forces in the roof structure through force diagrams without using the mathematical techniques they had been taught in their structural analysis and design courses. This was the beginning of intuitive design in this project.

As the lectures progressed, so did some of the students’ excitement and their willingness to experiment with new and different ideas. These students evaluated the advantages and disadvantages of pre-cast construction. They looked at ferro-cement as a possible building material, and they each evaluated a number of different ways to create the roof system necessary to cover the facility they were designing and at the same time produce a system that was elegant in design and could become the architectural statement for their building. However, while a number of the enrolled students were experimenting, the remaining students continued to design using standard structural systems and construction techniques. These latter students simply didn’t want to vary from the safety of the mathematical formulas they had been taught in other courses. Out of a class of fifteen students, eight investigated innovative and intuitive systems for their buildings, while the remaining seven did not.

Once the preliminary schemes had been presented and approved, all students began an engineering analysis of their system to both ensure it was a structurally sound system and to produce preliminary member sizes suitable for input into a computer structural analysis and design program. However, again the instructions were to analyze the structures using intuitive methods as well as only basic mathematical manipulations. In this way the students were required to study their systems in depth and to break each system down into the most basic component parts. Using these instructions, a number of the students did an excellent job of analyzing their structures and modified their final designs to improve the architectural appearance of the building significantly.

An example of a project that met or exceeded the expectations of the course was a new Air and Space Museum for the Pacific Northwest area of the United States. The structural system for this facility
was in the form of a torus with one section cut out to provide a major entrance to the facility. This building was four stories high, and the shell surface was formed by a series of interacting arches forming a geodetic pattern (diamond shape). The material used was steel with individual segments of the arches formed on the ground and then raised into place with a minimum of form work. The student analyzed the structural system as simple arches with the loads distributed to each arch intersecting at each point on the surface. Based upon this analysis, preliminary member sizes were determined and subsequently entered into a standard computer based space frame structural analysis and design program. At the completion of the computer run, the preliminary sizes were compared with the final design sizes. This comparison indicated that the techniques used by the student to do his preliminary design were very accurate. Actually, the preliminary sizes could be used and would have been a successful design. However, we still recommended to the students that a final design, utilizing state of the art computational methods and material codes be performed in every case.

Conclusions

This was an interesting course to teach. Slightly over half of the students accepted the techniques being presented and move ahead with innovative and well designed projects. These students were very pleased with the course and provided excellent course evaluations.

The remaining students had various reactions to the course. A few stated that they thought they were ill prepared to deal with structures of this size and had a difficult time handling the intuitive design aspects of the course. A few simply wanted to use the techniques they had been taught and let the computer tell them whether the system would work or not.

Since the course was first taught during the spring semester last year, it is being taught for the second time during this current semester. Projects completed last year have been displayed a number of times during the past six months so this year’s students entered the course knowing what to expect. The numbers are down somewhat this semester; however, all of the students are excited about the requirements of the course and are eager to continue. At the time this paper was written, the lectures were about half over and the student designs were improving at every meeting. That was very encouraging.

As a final note, one of the graduates last year took a job with a large, national firm that specializes in the design of large span structures. He was placed in the firm as a junior designer because of his experience in this particular senior course.

Based upon the success of last year’s experiment and the expectations of the course this year, it is anticipated that the basic concepts of incorporating historical lectures in a senior capstone course will be continued.

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