Less Is More: A Design-oriented Approach to Teaching Structures in Architecture

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Introduction

We are all familiar with the main issues that haunt structures courses in architecture schools:

- students struggle to understand statics and with applying mathematical procedures to solve structural problems;
- there is inadequate time to teach statically indeterminate structures and other systems that are a bit more complex than simple beams and columns;
- there is a perceived separation between design disciplines and structures courses.

The design studio is normally the focus of architecture students, and structural design is seen as something so different conceptually, that it is left out of their design process altogether. As Richard Bender put it: “The classical sequence of presenting statics, strength of materials, analysis and ‘design’ may represent a logical progression of information. However, divorced as it usually is from involvement with the total process of design, this sequence has resulted in architectural graduates who have no understanding of the basic principles involved, cannot apply them, nor retain for a significant period after graduation the basic core of material encountered.”¹

One way to make structural systems part of the "intuitive" design vocabulary of architecture students is to remove structures from the abstract realm of mathematics and bring it into the context of building design².

Like in any design field, structural design is not a precise science: instead, it is an art that requires initial assumptions based on experience. Students should understand that decisions on the structural system often have to go through several iterations before a precise solution is finalized. There are similarities and differences with the architectural design methodology, but there is a strong interrelationship with the building design process in terms of selection and configuration, and certainly in the architectural use of structures. The initial steps of structural design go hand in hand with architectural decisions, and they are the most interesting and potentially creative.

There are two approaches to bring this structural creativity into the studio: one is to make structural design an integral part of the studio problem statement. The second, which is equally important, is to introduce a degree of "realism" into the structures courses by teaching around a building design project. The "structures project" has some resemblance to Edward Allen's "second studio" idea³, with emphasis on system selection and configuration, but also on the understanding of structural materials, connections and member sizes. The understanding of the structural behavior of systems, which is obviously important for system selection purposes, can be significantly facilitated by the use of structural analysis software, allowing the students to understand the behavior of complex systems and test alternative configurations in order to refine their design solution.
The structures project: emphasis on integrated design

Since 2001, the "structures project" has been a feature of the structural design sequence I have been teaching, covering steel, wood, and concrete systems. It is now part of the fourth year structures course, in a revised curriculum, which includes concrete, wood and masonry.

In the structures project, students are asked first to configure a system in the context of a basic architectural brief. Then each primary element of the system is analyzed, members are sized and connections designed. Typically the brief requires the structure to be exposed, so that member shapes and connections became architectural design problems. Over the years, the structural systems designed have been mainly steel and wood long span, and steel and concrete multistory frames (Fig. 1). In both cases the system can be statically determinate or indeterminate. In the steel structures course, both long span and multistory frames were statically determinate; in the following course the project work has included a concrete rigid frame, providing the opportunity for comparisons with a steel system. The introduction of statically indeterminate systems has been the major innovation in the course content (versus methodology), and it has been made possible by the use of engineering software.

This approach addresses one of the somewhat surprising student attitudes: the idea that in a structures course they are not designers any longer, but only formula solvers. There is a frame of mind in the student sitting in front of his/her structures assignment (which would deserve some psychological attention), that makes the students forget how to draw and design, or think that, because it's not studio work, their drawings can be sloppy. It has been a constant effort in my course to make the students sketch (Fig. 2) as they think about the structural problem, versus jumping straight into the formulas. Students are also asked to submit structural drawings with the same graphic quality (and probably more precision) that they would adopt for a studio project.

Having the type of system as a given (e.g. a concrete braced frame), there are two
things students are asked to address as they first approach the design of a structural system: the configuration and the construction. Both have to do with loads and with the understanding of how loads are transferred to other structural members as they travel down to the foundations.

Loads seem to be one of the hardest things for students to figure out, but is this also one of the most important aspects of structural design: statics calculations can be perfect, but if the loads are wrong the results will be wrong. Making decisions about construction and sketching a wall or roof section helps the students to understand how loads are supported, and allows them to relate better to building technology and architectural design (Fig. 3). One could say that an understanding of structural design is not complete when divorced from knowledge concerning materials and methods of construction.4

The design process for the projects is paralleled by the introduction of related topics in the lecture course. In the case of a steel long span system, for instance, the first members to be designed are the roof joists, so the course deals at that point with simple bending members. The design and the course material then proceed with the design of beams, columns, tension members (suspension or bracing), and finally connections (welds, pins, bolts, plates) (Fig. 4). As mentioned before, the students are asked to look at the details of the structure as aspects of architectural design, and therefore the solutions must be elegant and well presented.

The design of a steel staircase is one of the opportunities to engage in some structural/architectural details (Fig. 5). It is probably the first time students are made to think about the components of a staircase as structural systems: the stringers, the...
treads, the railings, and the mountings, each subject to code requirements.

**Structural analysis software: emphasis on "systems"**

In the current upper level course (ARCH 418 Structural Systems 3), the concrete frame project is a way to introduce statically indeterminate systems (Fig. 6). Using a design project to discuss this topic helps the students to ground it into something concrete (pun unintended). The behavior of rigid frames is explained visually with a series of *Multiframe* workshops, starting with simple systems like portal frames and continuous beams. The first two or three weeks of the project are spent configuring the system, calculating the loads on the beams, and analyzing the frame to obtain the moment and shear diagrams with alternate loads (Fig. 7). Students then, as in the projects described before, design the main structural members (beams, columns, footings, and others) including the steel reinforcement. One of the primary issues is to make students understand the concept of continuity of the frame, reflected in the way the steel bars are placed at the columns (Fig. 8).
The design of the shear walls is one of the major issues in terms of integrated design, and inevitably revisions of the floor plan are necessary at that point (Fig. 9). The design method for the shear walls is kept simple and does not require the use of the computer, but it is an opportunity to discuss the frame behavior under lateral loads without shear walls, which can be easily done with Multiframe.

There seems to be some degree of consensus that the main objective of structures courses should be the understanding of structural behavior. A 1995 survey\(^6\) indicated that the two primary objectives of structures courses were the qualitative and intuitive understanding of the behavior of building systems, and the quantitative (mathematically based) analysis skills.
Computer analysis is used in the course to teach about other systems, such as arches and domes, in addition to suspension systems. For a steel system, the software has the ability to calculate and visualize the deflections, offering an additional tool to study the optimal configuration and combination of member sizes (Fig. 10). The students can also understand how the deflections of the long span beams in a suspension system depend on the behavior of the entire system, including the deflection of the columns and the elongation of the suspension rods. This type of holistic view of the system would be very problematic for students if approached with the traditional tools and methods.

One of the possible criticisms of using computer software to solve problems of statics is the "black box syndrome": the computer analysis produces results the students have to use blindly, without understanding how they are worked out. In order to accept the computer as a valid pedagogical tool, we first must ensure that the students are introduced to statics and have a basic understanding of internal forces and deflections. After all, we accept similar methodologies in studio: perspectives, for instance, are today generated by computer (and are much more sophisticated than what students could do by hand). This is acceptable because the students are first taught the principles and methods of perspective drawing. In fact we understand three-dimensional digital modeling as a different, more potent tool than conventional perspectives to investigate complex issues like light and movement in space. Similarly, computer modeling of structural systems can be a heuristic device to test ideas that could have hardly been understandable by an undergraduate architecture student before. The way students (and I'd say professionals) calculate structures is, after all, full of "black boxes": from deflection diagrams to code formulas for which we rely on ACI, AISC, AITC, and other professional institutions. We can accept these "black boxes" in our design process because we understand the principles that lay behind, and know when those formulas are applicable. In an architecture course, students can use structural software to go a step further. The use of the software is not just to produce design solutions, but to understand more - and with less effort - about structural systems and the structural design process.

Conclusions

Of the three innovations introduced in our structures courses, two are about method - the project and the computer analysis - and one is about content - statically indeterminate systems. The methodology
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has allowed to enrich the course content and to reach the two primary objectives:

1) enable the students to see structures as part of the design disciplines, and part of the architectural design process;
2) enable the students to learn about complex structures previously considered to be beyond their ability but, at the same time, very common in practice (such as rigid frames).

Before I introduced the use of computer analysis, we had four structural design courses, and there was not even the mention of statically indeterminate systems. Students would graduate without any conceptual understanding of rigid frames or continuous beams. Now we have reduced the structures sequence to three courses, and yet students are able to discuss a multistory concrete frame and even design the structural details.

Not all calculations are done by the computer: students are asked to go through the sizing procedures the traditional way (code formulas, pocket calculators, pen and paper). However, the most complex statics calculations are relegated to machines, as Leibniz was trying to do by inventing a mechanical calculator in the seventeenth century. Because the course is not really about statics but about design of structural systems, students can focus on the understanding of principles and processes of structural design. This helps the students to see the mathematical calculations not as an end to themselves but a design tool. This experimentation is addressing a number of pedagogical issues and leaves some open questions:

- The attempt to reach the studio from the Structural Systems course should be mirrored by the same effort in studio so that, at least at some points, the two courses can hold hands together. The problem, however, is that in a fourth-year studio the architectural design work is likely to require very complex structural solutions; in addition, it is practically impossible for one structures instructor to follow the individual work of six or seven different studio sections with a total of over eighty students.

- There should be a more systematic exploration of engineering software and its appropriateness for the classroom, eventually resulting in writing structural software packets for educational use; the applications should not be limited to statics but could also deal with databases, graphic representation, and integration with architectural CADD software.

- We should eventually find a way to assess the integration of structural knowledge and architectural design in the studio work of the same or following semester.

In my experience, the teaching of structures as a design discipline can be eventually more effective than teaching technology in a studio, with technology "support" courses. A structural design course using design projects can provide the necessary degree of "rigor and depth required for effective integration [of technology in the design process]". At the same time, the design studio is an excellent teaching method to follow, because it works based on the principle that students truly understand only what they discover for themselves. The same discovery approach could be used in teaching structures; the reason this does not happen in conventional courses is because of the mathematical complexity of structural analysis once we go beyond the most basic systems. The software effectively allows using an empirical method to explore structural behavior, by testing alternative configurations and comparing force diagrams and deflections. It is easy to demonstrate how in statically indeterminate
systems the relative rigidity of members alters the distribution of internal forces. This approach is similar to testing physical models, which can give a measure of the stability of a certain configuration or of their strength as visualized by deformations. However, computer modeling gives much more information with much less demand on time and resources compared to physical models. Both the project and the use of Multiframe have been extremely well received by students, as evidenced by evaluations during the course (with specifically targeted questions) as well as the semester-end evaluations, and this can be a first (but only partial) measure of effectiveness. The results of this methodology can be summarized by paraphrasing the famous sentence by Mies van der Rohe: "less is more," or less time can be devoted to toil on statics and calculations, while the students acquire more knowledge about structural design and more understanding of how it is relevant to architecture.

Notes:


2 This topic has been amply discussed by James Ambrose, Teaching Structures. 1994: New York, distributed by Wiley (unpublished manuscript).


4 This is paraphrasing a statement by Ryan E. Smith in his article "Bridging Structures, Construction and Studio" in Connector, Vol. XIII No. 1 (Spring 2004). The objective of the technology course described in this article is to make students discover the logic of space organization intrinsic to a construction system, reversing the common design process, which goes from space requirements to construction system.


6 Faoro, Daniel. “ACSA Structures Curriculum survey.” 1994: North Dakota State University (unpublished). Results indicated that the two primary objectives of structures courses were the qualitative and intuitive understanding of the behavior of building systems, and the quantitative (mathematically based) analysis skills (Question 11). Question 13a was a review of software specific to structures courses.

7 “For it is unworthy of excellent men to lose hours like slaves in the labor of calculations which could be safely relegated to anyone else if machines were used.” Gottfried W. Leibniz, De Progressione Dyadica, Pars I, (MS, 15 March 1679), published in facsimile (with German translation) in Erich Hochstetter and Hermann-Josef Greve, eds., Herrn von Leibniz’ Rechnung mit Null und Ein (Berlin: Siemens Aktiengesellschaft, 1966), pp. 46-47. English translation by Verena Huber-Dyson, 1995. An interesting discussion of this idea by George B. Dyson can be found at The Reality Club, www.edge.org.

