Architectural Structures:
Tools and Articulations

RICHARD FARLEY
University of Pennsylvania

> Therefore I feel one has to start on the concrete and slowly converge with the abstract, but always keeping your eye on how the symbolism works with fact.
>
> – Robert Le Ricolais

The study of structures is a comprehensive discipline encompassing the effects of gravity, wind, water and earth movements in the placement of and assembly of structural components into building systems. This disciplines fostered in architectural education, is predicated on the knowledge of typology (loads, elements of structure, gravity and lateral structural systems, materials) and judgment (application and appropriateness of structure). Acquiring structural tools provides the architect with the ability to articulate well-scaled and configured designs.

The goals of the course are specifically aimed at developing an understanding and intuition of structural behavior, an understanding of structural materials and their relationship to the building process, an exploration of the relationship between architecture and structure, and an examination of forms which are architecturally well-integrated (implicitly or explicitly). This approach was introduced to the curriculum by Peter McCleary, who teaches the advanced courses.

The first semester looks at architectural structures from the "inside out" focusing on the elements that compose skeletal structural systems. The elements of structure (beam, column, truss, and frame) are examined and mathematical methods for sizing are taught, including the rational basis for factors of safety. The students are taught the performance of the structure—exhibited by points of contraflexure, zones of tension and compression, shear, deflections and rotations.

The second semester elevates the skill level of the class. The building structure is considered from the "outside in". The typologies of surface structural systems are explored, including curved structures of vaults, domes and shells. While the first semester is centered on static conditions, the second semester introduces the fourth dimension, time, to structures. The effects of dynamic loads due to seismic, wind and water forces are shown, especially for lateral load-resisting systems (rigid frames, shear walls, and braced frames).

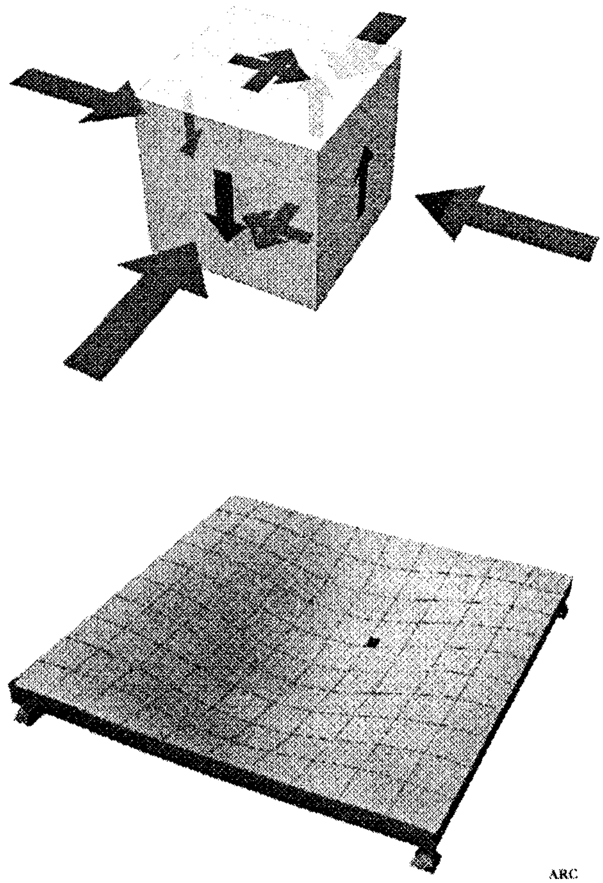

Fig. 1. Illustration showing a uniformly loaded slab, indicating the direct stress due to bending and shear stress on the indicated point in the slab.

The lectures establish an understanding of the basic principles of structure for various types of systems, elements and materials. The theories and principles lead to tools for calculating the size of structural elements for architectural designs. Preliminary design information (sizing calculations and material data) is developed for each of the elements of structure.

JUDGMENT OF STRUCTURE

A collective experience and wisdom is brought to the graduate program by the students. Drawing on this, the lectures are organized to be highly interactive, challenging the students to articulate their opinions and observations on appropriate design limits, rational bases of acceptable practice, speculation of deflection, deformation and sizing. Interchanges range from queries on advisable acceleration and structural drift to the symbolism behind Newton's apple and Hooke's serpentine spring.

In counterpoint to the lectures, the course presents the students with exercises that challenge their judgment of structures. These exercises include:

- structural evaluations
- "ideal beam" competition
- framing problems
- construction site trips

Structural Evaluations

The Penn legacy and body of work (readily accessible in the architectural archive exhibits) of Paul Cret, Louis Kahn, Robert Le Ricolais, August Kommendant, and Harry Parker are introduced and evaluated, as are the significant edifices of architectural history including the work of Maillart, Gaudi, Nervi, Foster, and Calatrava. The students are questioned regarding their opinion of these projects and the appropriateness of these structures.

"Ideal Beam" Competition

In Le Ricolais's words, the competition seeks "the art of structure — to achieve zero weight and infinite span." This assignment is met with incredible enthusiasm. Working in teams, the students construct beams to carry a concentrated load at mid-span. The beam is simply supported. The students predict the type of failure and load at which it occurs. The team that achieves the best ratio of load to structural weight wins the competition. A deflection gauge is used to note the flexibility of the structure, and special note is given to the beam that performs the best in this regard. All beams are tested to failure. The winning ratio is typically in the range of 1:1000.

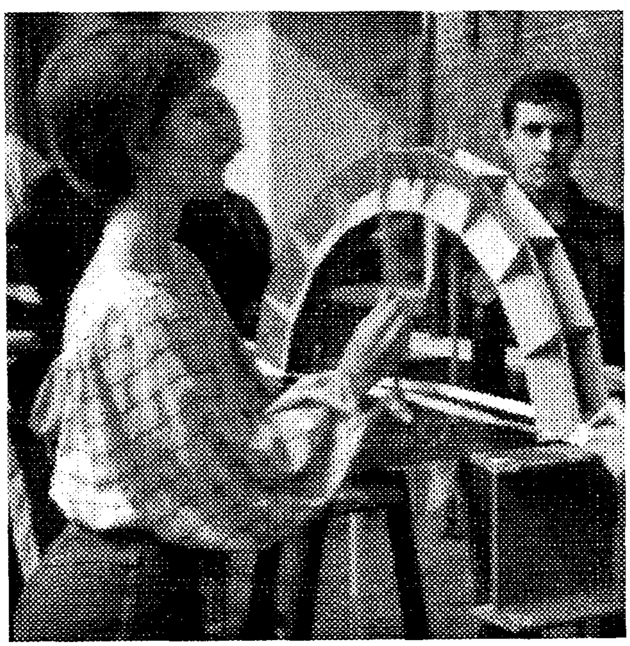

Fig. 2. "Ideal beam" testing to determine the lightest beam that carries the greatest load before failure.

Framing

The framing exercises directly parallel the structural issues experienced in the design studio and serve as a reference for integrating structure into architecture. The structural tools are tested in building framing exercises which challenge the students to make judgments leading to the appropriate use of elements of structure and materials into building structural systems:

The Barn

Framing diagrams are prepared for a series of architectural sketches of amulti-level barn. While there is no limitation on material, the preference for wood is noted. The barn design shows a series of conditions that need to be reckoned with, such as an exposed basement on the east end, an overhang without column support, and loft openings on the end walls directly below the ridge of the roof. The students work to frame the structure and invariably question the architectural design, noting that it compromises their quest for a straightforward framing scheme. At the conclusion of the exercise, the various schemes are discussed. Ultimately, a framing plan is generated by the class that completely respects the original architectural design. A great deal of structural skill and finesse is required to accomplish this. In subsequent studio design problems, and indeed throughout their architectural careers, the students will be in the reversed position of being the architect controlling (and sometimes defending) the architectural design and the demands it places on the configuration and size of structure.

The Church

An advanced laboratory assignment is given to further develop skills after seismic and wind loading concerns are taught. Using computer modeling, gravity and lateral loading conditions are studied for a steel structure forming a church. A lateral load system is devised for the mutli-bay, one-story nave and also for the bell tower. The effects of modifying the type and placement of braces, shear walls, and rigid joints are compared. The resulting drift dimensions and weight of the structure are analyzed to select the most efficient configuration for the architecture.

Site Visits

The buildings, construction sites, and fabrication plants surrounding Philadelphia have provided the course with an extensive "reference library" for instruction. The professor

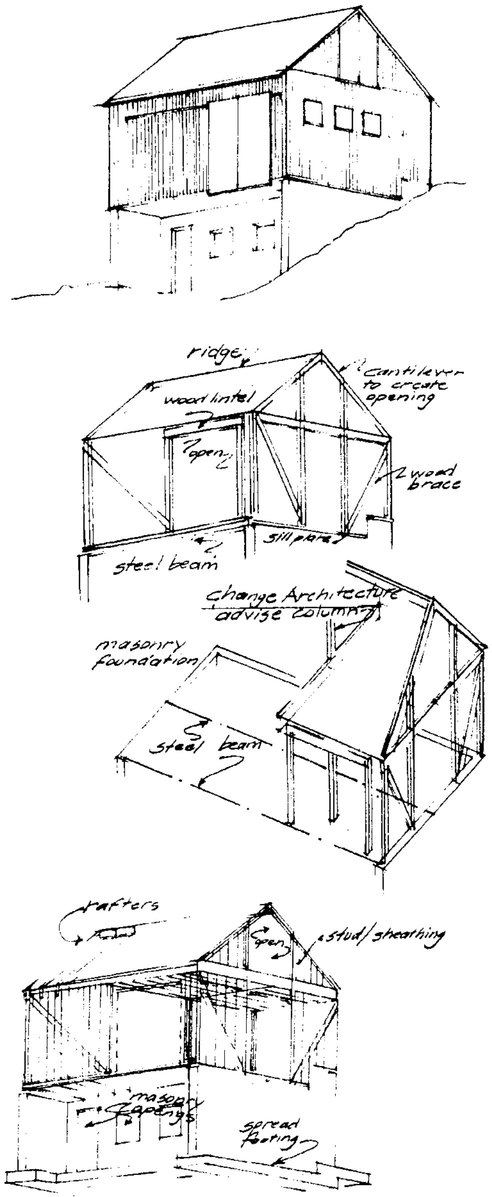

Fig. 3. Illustration of a framing exercise for a small building.

obtains detailed knowledge on the construction for each site visited (often they are his projects). The students learn the particulars of connections, soil conditions, foundation selec-

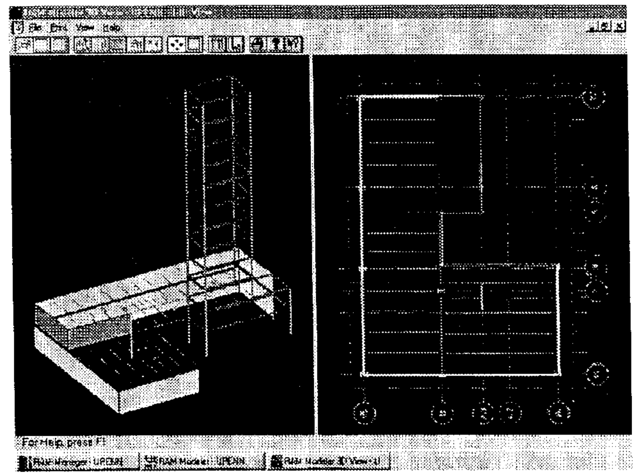

Fig. 4. Illustration of a computer generated structural analysis framing model.

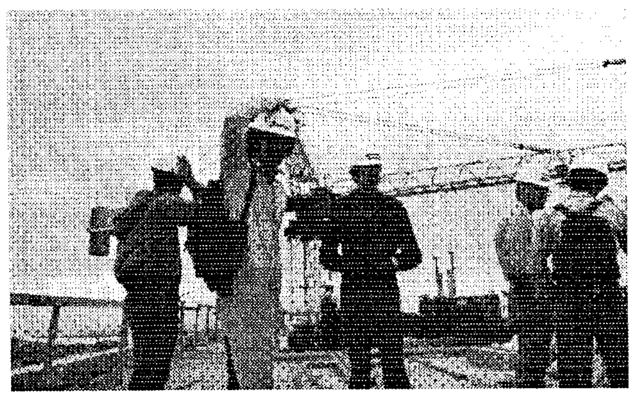

Fig. 5. Field trip to a cast-in-place concrete high-rise structure

tion, seismic considerations, and construction issues. Our students have stood atop skyscraper frames, witnessed the placement of long steel bridge girders, and observed the casting and erection of precast elements.

Once, in sub-zero weather, watching a long span precast member being cradled onto a truck for shipment, a student noted his fascination with precast elements, but proclaimed that he would never put that aggregate choice or member shape on a building they designed. Typology and judgment, indeed!