Physical Models in Teaching Structures: From Basics to Creative Explorations

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PEDAGOGICAL ISSUES AND METHODS IN TEACHING STRUCTURES

Innovation and Self-discovery

The purple Jell-O cylinder bulges from its own weight, demonstrating compression. A small heart-shaped paper strip floating in a pan of dish washing soap and inflated from below becomes the rim of a pneumatic valentine—the funicular form of the given boundary. Plastic wrap works as a form liner in precasting of frames. No amount of foresight and prescriptive instructions can anticipate such demonstrations and answers to building problems. The challenge of the investigation draws upon the collective wealth of student imagination and resourcefulness.

There is no substitute for the sense of satisfaction that comes from resolving a problem. Others may have done this before us, even better, but in learning, coming upon a solution is more meaningful than being handed the answer. A discovery of what the "experts" know brings personal reward; a taste of the process of creating knowledge builds self motivation. Teaching limited to the transmission of knowledge is not real teaching. Learning confined to retention is not lasting learning. The teacher of structures shows the route to decision making just as the master establishes the discipline of the Way. This road to an "enlightenment" is a lot more prosaic, but it is similar in its reliance on self-learning.

To repossess a fact or rediscover a method has a powerful and lasting impact that is not easily lost. It is an extremely effective mode of learning. No amount of reading, observation of visual material or even real structures can substitute for the experience of discovering structural behavior. The many observations and unexpected quirks encountered while making something stand up are more important than the final accomplishment.

A few introductory lectures deal with the purpose of structure, the role of mathematics, and basic structural phenomena, such as stress, bending, equilibrium, and stability. The responsibility of architects and the relationship with engineers is illustrated with personal experience and anecdotes. Structure systems are categorized according to their behavior rather than material, and each system is introduced with slide lectures. Lectures cover the principles, criteria, and the unique qualities and limitations of the structure system. Examples range from nature and artifacts to ordinary applications, key built structures, earlier student experiments, and theoretical studies. The intention is to inform as well as to stimulate, and special focus at times is given to membrane materials or prestressing. Special events, such as lift-slab construction call for a field trip, and beginning students may build a full-size structure. There are a few good films, and students are provided with a reading package and an extensive bibliography. The models, however, constitute the key learning vehicle.

The Role of Models

The behavior of structures can best be understood through models. Search and experimentation during the process of achieving a particular structural goal provide immediate, invaluable feedback. Vibrations can be felt, gradual transformations observed, rotation or imminent collapse checked, tension or compression visualized and ascertained as well as stability tested and proportions scrutinized. A physical model is the most effective way to represent the form of a structure, however, representation is only the final and often surprising phase in the process of search and discovery.

Such learning must be facilitated and carefully guided through exercises with well defined goals and parameters. The primary intention of an assignment is generally accompanied by several secondary requirements. Stabilization of a framework, for example, must be done with the least amount of material and be well crafted and pleasing to the eye. A checklist of questions about the process and product serves as criteria for the exercise. References are useful in advanced structural development projects but not in simpler studies intended to disclose the inherent principles of a structure system. Precedents tend to contaminate and channel the exercise, and it is more instructive if the student is not object fixated.

Learning and Evolution of Structure

Some of the structure systems considered novel thirty years ago are now commonplace, but the evolution of structure compared to other sciences is rather slow. Pushed to an extreme, several structure types manifest an interesting convergence, but this is a topic for another study. Behavior of structures is still limited to the same fundamental groups.[1] The teaching of structures,[2] however, remains as much a challenge as it was decades ago.

Some of the obstacles are cultural, such as those encountered in working with the Chinese students of Hong Kong, and too difficult to fully understand and generalize in absence of an interdisciplinary study. Suffice it to say that the teacher can never relax and assume that the methods will always work. Techniques and goals, of course, must also vary with the year level, but most exercises and studies are equally valid and rewarding at the beginning, intermediate, or advanced stage of the student's education. Few have ever had such exposure to structural decision making and creative exploration, and the theory of structures courses fail to instill an intuitive sense of the behavior of most structure systems.

Creativity in Structures

Understanding of the behavior and the structural mechanism of each system is a prerequisite to creative use of structure in architecture. Yanagi said it very well:

> "Laws exist in a realm that transcends the self and ownership. Laws are the work of nature, not the product of human ingenuity. It is nature that makes laws work. To observe them is appreciation. Neither is a matter of the maker's intellectual ingenuity."[3]

Reduced to the simplest possible form, structure becomes an irrefutable manifestation of a principle, and its beauty is indisputable. This is a start, but the prototype or an assembly of a self-contained fragment needs to be applied to a complete structure, and the interdependence of these assemblies results in a transformation.

What then is creativity in architectural structure? We live in a culture that places great value on the individual and the stamp of personality. Freedom of expression should not be confused with license. It is not possible to deconstruct a truss without suffering a penalty. Creative development of structure calls for transcendence rather than a negation of personality. It takes great personal strength to go beyond the insistence on individualism.

Model as Guide

The presence of the initial model and the experience with building it provide the direction for further development. Usually repetition is impossible without an accompanying change to the assembly. Alternatives are considered and the work proceeds through trial and error. Each new phase presents additional problems, yet what has been accomplished also guides and channels the work. Everything depends on the builder's sensitivity and ability to read the clues. This is not so different from a building design process except that the structure itself, rather than a program, sets the agenda.

This is best observed in work with children. A simple wood beam placed on two posts becomes a prototype for a series of parallel posts and beams. The available planks suggest the spacing between the beams. Most architecture students are too bored with such rudimentary structures, but did we not spend months building towers from dominos during our childhood? Given a kit of parts, first-year design/structures students follow this same path.

STRUCTURE SYSTEMS AND THE DEVELOPMENT OF A KNOWLEDGE BANK

Experimentation without direction and guidance does not work. Extremely few students can become fascinated with some notion of structure, as they have little to build upon. It is best to construct and evolve the knowledge bank step by step with an overview of the range of structures as a goal. There are two sides to this build-up: the intrinsic behavior of each family of structures and their design implications and place in architecture. Furthermore, in building structure seldom exists by itself. Spatial and functional requirements, the need for light, mechanical service systems and the degree of their integration are but a few of the determinants in our choice of structure. Material preference and construction process, likewise, articulate and particularize the abstract structure system. Such a survey equips the student with a comparative basis for making decisions; the strengths and limitations of each structure system are now linked to architectural space and form.

It is not possible nor is it necessary to dwell on all the formal possibilities while describing the strategy, method, and exercises used to teach a course on structure systems. Each structure system presents distinctly different issues and challenges peculiar to the particular system. I will refer to the merits of a particular structure only in relation to the pedagogical goals. Due to space limitations, only a selection of exercises will be described.

STRUCTURES TRANSMITTING FORCES THROUGH FORM

The primary members and components in this group are in single stress—tension or compression. It is easier to begin a study of the behavior of structure systems with this family rather than with bending resistant structures—the most common structure type.

Cable Systems

Stabilization of a set of two to three cables suspended between posts provides an exposure to the direct relationship between forces and form. This project can be successfully done with first year as well as more mature students. A single cable is unstable and unable to resist oscillation, although many architects did not seem to realize this in the 50's. The task is to come up with a prestressed assembly able to maintain a stable form and dampen vibrations. A span of two to three feet is convenient, and a solid base is indispensable.

There are two ways to prestress the cables—either by pulling them together or by spreading them apart, and it is also possible to combine the two. An assembly of three suspension and stabilizing cables results in the optimum condition, but resorting to a warped surface is an ingenious way to eliminate flutter.

Placement of posts in sockets simulates pin connections. Such posts can take on the optimum angle in relation to the anchoring points of the cables. Some suggestions are made prior to the assignment, and the solutions lead to discussion of the consequences. Cutting away the superfluous or unstressed cables and the removal of redundant compression members add drama.

The advantage of this exercise is the immediate feedback during the process of building. Each added cable or strut, points of support and so on has a corresponding structure form. If time permits, this project can be followed up with the building of part of a larger structure which calls for solving the interaction between the assemblies.

There may not be a more humbling experience than the building of a tensegrity structure. Tensegrity has yet to find convincing application in architecture, but it is a marvelous device for putting the ego in its place. There is only one possible state of equilibrium for a given condition, and I know no better way for reaching this understanding. Jigs and instructions have simplified the undertaking. Even beginning students could do these, but the pedagogical value is by far the greatest with advanced students. The apparent defiance of gravity counters the rigid attitudes acquired through some of our "rational" courses.

The building of rotational, two- and three-directional cable structures, and cable nets requires considerable planning and is best suited for students who have done the beginning projects.

Tent Systems

Cables condensed become fabric, and this is a convenient way for seeing the transition from linear tension elements and cable nets to surfaces. The tent membrane must be prestressed in order to resist external forces. The fundamentals of tents can be mastered in 15 to 45 minutes. Due to the need for pattern making, tent is the hardest structure to design, but the principles can be easily understood using stretch fabric. Nylon hose is a particularly convenient material for this project.

Only warped surfaces can transmit tension and resist wind loads—the major forces affecting light-weight structures. Flat areas are to be avoided as much as possible, as the membrane would have to be infinitely strong to maintain this shape. Thus, 45° to 60° angles are most effective, and the edge of tension membranes is scalloped.

A fan is used in the review of these projects. Flat areas, unstretched loose fabric, unresolved boundary conditions, or improperly anchored posts will vibrate resulting in impact load. An unloosened point of anchor provides a spectacle of structural hazards and drives the point home.

Follow-up projects can integrate other structure systems, such as arches and cable nets and refine struts, masts, and foundations, or focus on an erection sequence or convertibility. Architectural space and functional requirements, relationship to landscape, ventilation, lighting, thermal loads and similar issues can be addressed more appropriately in a special design studio.[4] Key tent structures, such as the Jedda air terminal in Saudi Arabia, provide convenient departure points for alternative studies.

Pneumatic Systems

It is much more difficult to use models to study pneumatic structures, and this exercise needs to be closely directed. The results, however, may be well worth the effort. Students are advised to start with commercial products and to modify these with external cables and peripheral conditions, thus eliminating the need to make seams.

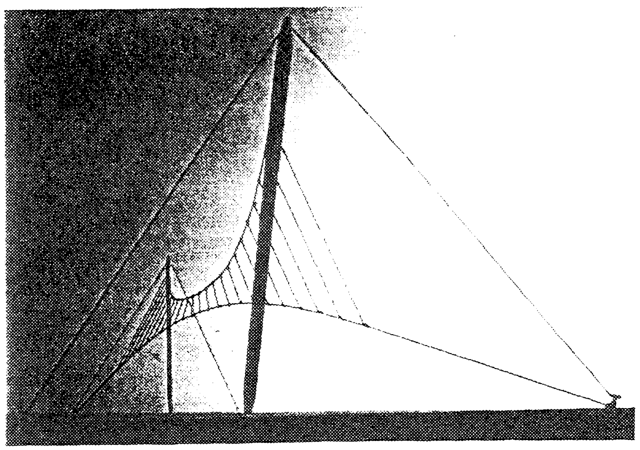


Fig. 1. Stabilization of a suspension cable [Roberto Campoamor and Halcyon Haynes-Campoamor, University of Oregon, 1981].

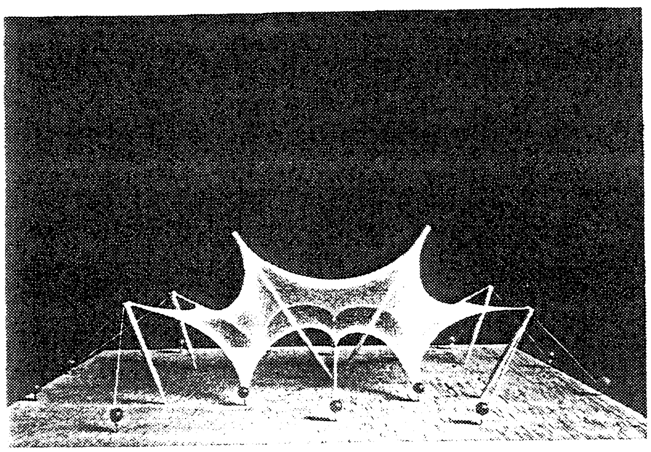
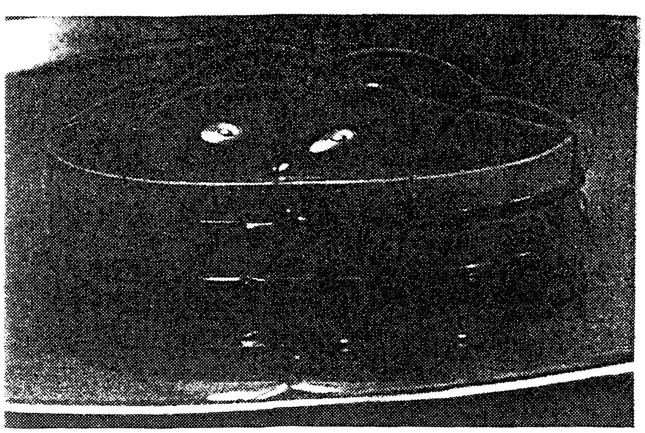


Fig. 2. Tent model by a first-year student. The tent membrane is 16 cm long. [Cathy Ng, Chinese University of Hong Kong, 1994].

Soap film discloses the optimum forms for given boundary conditions. It is a waste of time just to blow bubbles in the studio, as they have a very short life. A controlled scientific methodology is needed, and the process must be recorded with close-up photographic equipment.

Soap film techniques can be applied to large, low-rise pneumatic cable-net structures. This is an innovative method with potential application in the investigation of the funicular forms of pneumatic, tent, and even shell structures. The process is simple and even easy to use in the studio[5] and can be done on a pan of dish washing soap. A wide variety of little "cable"-net arrangements and rims can be floated and inflated. Students hooked on these experiments are hard to dislodge and move on to the next project.



Fig's. 3 and 4. A soap film experiment of a low-rise cable-net funicular pneumatic form [Joe Loudermilk, University of Oregon, 1980].

Arch Systems and Arched Wall Structures.

An arch is a rigid compression element and the reversal of a suspension cable. Consequently, it is more difficult to understand its behavior through the use of models. There are useful precedents[6] for assembling two- or three-hinged arches from separate pieces. The issues related to the requirements of arches can often be addressed together with tent, truss, or shell assignments.

Arched wall openings and historical masonry arches can be studied in model form, particularly in introductory courses. These inevitably include the construction process. First year student teams began by manufacturing one thousand wood bricks before assembling a brick structure, replicating the openings in Kahn's Institute of Management in Ahmedabad, vaults, Jefferson's curved wall, etc.

STRUCTURES TRANSMITTING FORCES THROUGH SURFACE CONTINUITY

This family of structures transmits forces through tension and compression but not bending.

Folded Systems

Prismatic folded structure systems are very common, particularly as small-scale building components. An origami inspired in-class paper folding session provides an introduction to minimal folded structures. These can include the necessary diaphragms and edge stiffeners. The methodology is applicable to beginning as well as intermediate classes.

Built examples of polyhedral surface structures are very uncommon, but the theoretical studies have proved to be

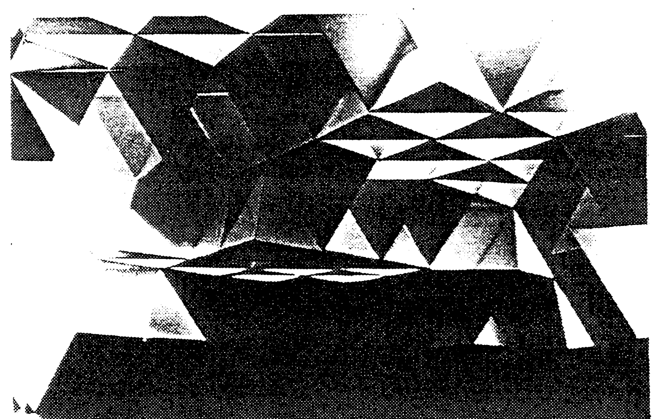


Fig. 5. Polyhedral surface structure based on tetrahedral and octahedral geometrical order [David Roth and Robert Metler, University of Oregon, 1972].

most inspiring to students. The possibilities with such systems are inexhaustible and remain largely unexplored. These projects require teamwork due to the time consuming cutting of cardboard. The project requires an ability to figure out complex geometrical relationships, but has the added focus on principles of order. Not all students, however, can handle such abstract investigations. This work is somewhat analogous to research in pure science.

Shells

There are three main shell types: singly curved, rotational, and anti-clastic. Projects can take two useful directions. It is possible to build actual thin shells, but the shell behavior is hard to observe, or the students can focus on the geometry that generates the shell, accept the fact that such models are only representational, yet be inspired by their formal and spatial possibilities.

There is a considerable range of choices. It is not difficult to build singly curved and rotational forms by curving paper or other material or by using a balloon to form a thin plaster shell or layers of plaster soaked gauze. The doubly curved anti-clastic hyperbolic paraboloids can be approximated by coating tents with latex paint or fiberglass epoxy, but this creates problems with the edges, or they can be built using forms, wire mesh reinforcing, and stiff concrete mix with scaled down aggregate.

The beauty of conoids, hyperboloids, and hyperbolic paraboloids lies in the fact that such shells can be defined and formed by straight-line elements. First year or advanced students can easily assemble a shell-like surface from paper strips, thin wood, or even hard spaghetti. Here the emphasis is on the generation of the form rather than simulation of behavior.

STRUCTURES TRANSMITTING FORCES THROUGH VECTOR SEPARATION

A triangulated assembly of co-active tension and compression forces results in a mechanism for load redirection.

Trusses and Curved Truss Systems

Truss behavior is discovered by suspending weights from an extremely light model. This truss mechanism illustrates the truss geometry, the distribution of tension and compression members, the transmission of forces, the problems with occasional lack of triangulation, the need to place loads at panel points, the issues governing supports and lateral bracing, and much else. Subsequent assignments may interpret this model through architectural form, the relative size of members, and the relationship between trusses and the enclosure system.

Not each and every truss member will show the stress, and some may get distorted due to lateral shifting, but the pattern can be easily observed. Compression members will buckle and the tension members can be felt if not seen. Here care in workmanship and pre-testing prior to the review is critical. Overbuilding the truss or placing it on heavy columns that induce bending and preempt the experiment are likely problems. Plastic broom bristles or model building materials are ideal, and thin wood, wire, even dried plant stocks and spaghetti will work. Soldering of piano wire may build in secondary stresses which are difficult to overcome. Most advanced students don't understand the truss despite their ability to analyze and size it, so this exercise works at all levels.

Curved truss surfaces, such as vaults, domes, or warped geometries are more goal-oriented towards a representa-

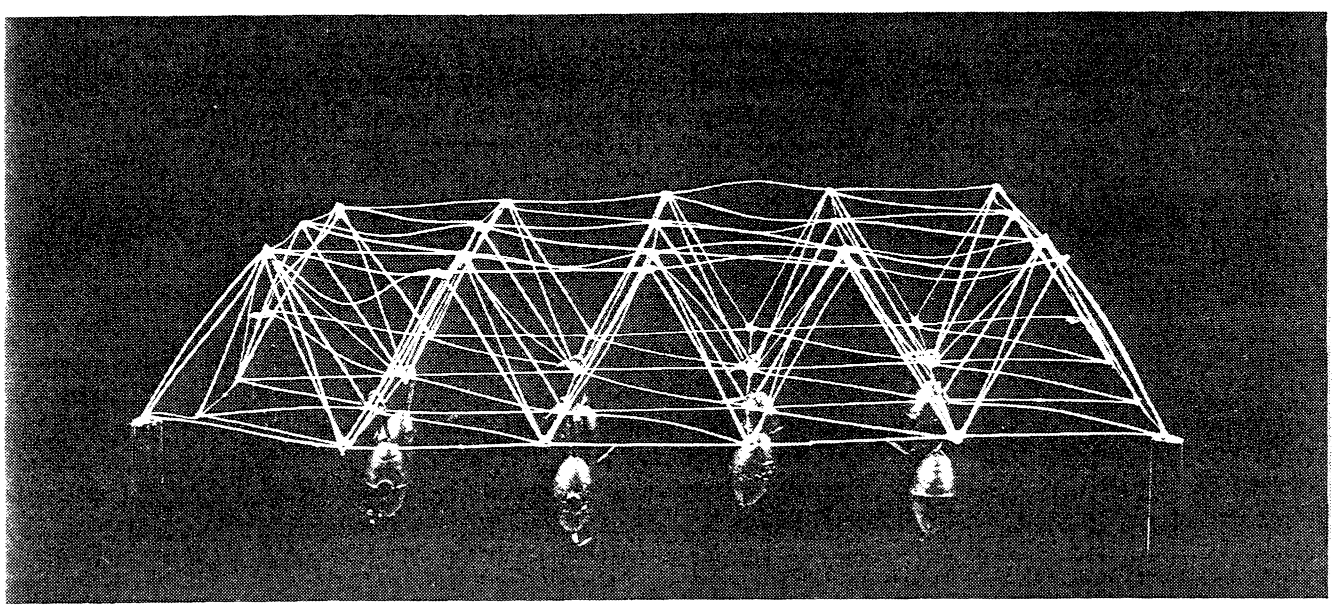
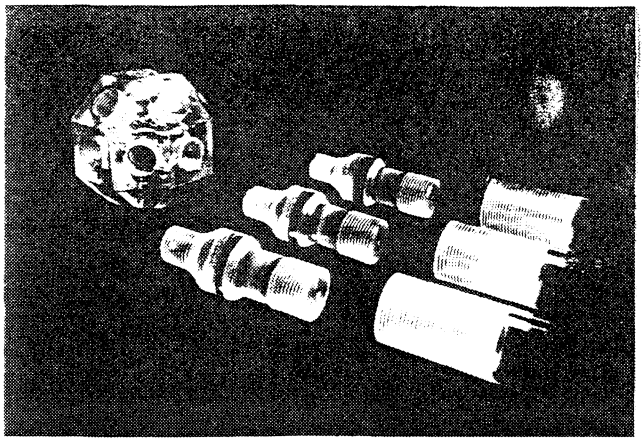
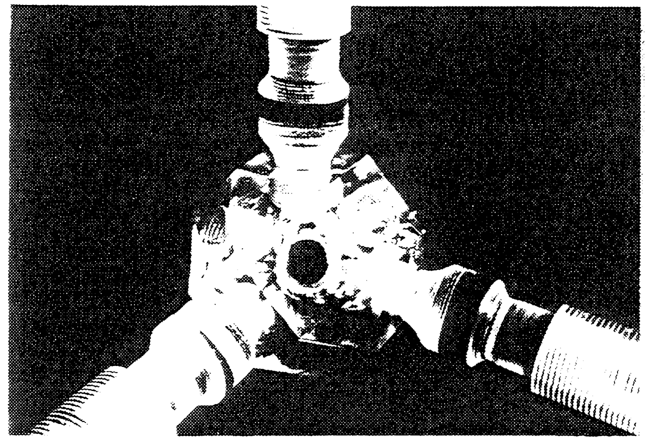


Fig. 6. Truss mechanism built with broom bristles [Hollain Lau, Man Cheong Chow and Wai Kit Lee, Chinese University of Hong Kong, 1995].





Fig's. 7 and 8. Cast and machined space truss connection as model for a steel connection, but this could also be a prototype for an acrylic display structure [Jay Pickering, University of Oregon, 1982].

tional structure and, thus, much less useful as learning experiences. Geodesic domes are particularly time consuming due to the chord factors, and such projects, unfortunately, tend to predispose the class to cult followers.

Space Trusses

No other structure system is as determined by the nature of the connection as the space truss. The joint influences its structural performance, aesthetics, assembly method, and much else. Concentration on the development of this node transfers care and awareness of details and workmanship to other systems as well. It is necessary to introduce first year students to the importance of details and craftsmanship, but this is a project more suited to advanced students. Emphasis can now be placed on choice of material and production methods, and projects can range from very simple cardboard studies to castings and machined parts. Some students can continue their explorations as special study projects. Students have varied backgrounds and skills, and a few are interested in fabricating full size prototypes.

STRUCTURES TRANSMITTING FORCES THROUGH BENDING

The most prevalent type of structure system redirects vertical loads through material mass.

Beam, Beam Grid, and Beam and Slab Systems

Visualization of basic structural phenomena is quite difficult, and understanding the complexity of bending requires a combination of methods. It is easy to observe bending by building and loading frameworks reduced to a minimum, similar to the truss mechanism. This method is applicable to all bending resistant structure types. A sequence of diagrams commonly used to isolate horizontal and vertical shear and bending moment is indispensable. Physical models are still more effective than computer simulations, as one can touch them, make small changes, and watch the transformations that the structure undergoes.

The challenge of this common structure system lies in understanding framing strategies. It helps to break this down into clearly defined goals, such as framing a square bay or a small structure. The task is cognitive in nature, but the model forces examination of the construction sequencing process, decisions related to spacing, and permits visualization of more complex multi-story framing conditions.

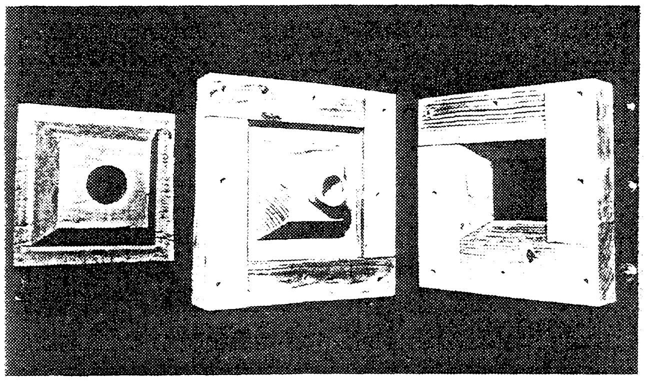
Learning from vernacular precedents works very well with first-year students. They are given information about historical or extant structures and asked to build a model. Finding natural materials in scale with the shelters, researching the construction process and life patterns provide a refreshing break from the other experiences.

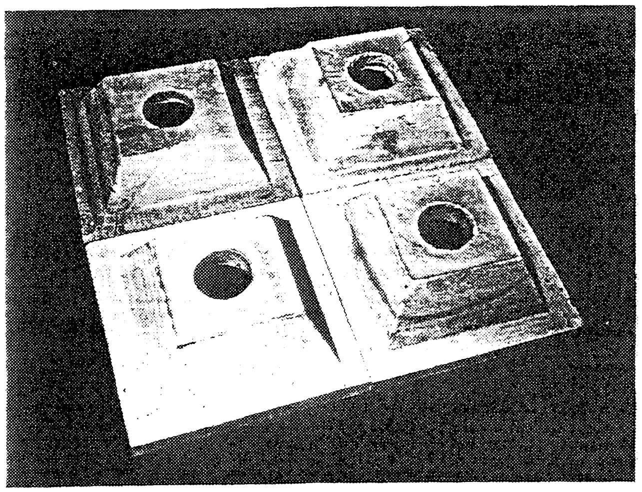
Rigid Frames, Vierendeel, and Space Frames

The emphasis on moment connections and material continuity has led to a very popular and satisfying but rather time consuming precasting project. Two and three-hinged rigid frames, Vierendeels, beam and slab coffers, as well as most bending resistant structures, are well suited for this project. This is a collaborative upper-level exercise that emphasizes the construction process. The design of the formwork determines the piece, and removal of the forms presents considerable challenge. Patching compounds, such as "Fixall" are particularly useful, but it is possible to use micro concrete, acrylic, plaster of Paris [too messy], dental casting stone, and other materials. Students tend to discover new possibilities. Reinforcing is placed inside the forms, and the elements may be grouted together or post-tensioned.

Multi-story and Vertical Structures

Multi-story structures integrate other structure systems as sheer walls or wind bracing. It is too time consuming to build models of vertical structures. The behavior, such as torque, can be conveyed through simple wire models. It is advisable to engage such a project within the framework of a design studio, and to confine models to a typical floor, the core, exterior wall, etc. in conjunction with other design issues.





Fig's. 9 and 10. Precast "Fixall" coffers for a beam grid structure system [Robert Hoffman and Keri Scarborough, University of Oregon, 1993].

CONCLUSION

Models are the most effective means of learning about the behavior of structure systems, and some structures, such as tents, can only be conceived through the use of real or virtual models. Only highly specialized consultants can mathematically analyze many structure systems, yet students can easily acquire a working understanding of all structure systems. The challenge in teaching structures is to develop self-directed learning strategies. Models open up new dimensions in learning about and experimenting with concepts of structure.

NOTES

[1] Engel, Heinrich, *Tragsysteme/Structure Systems*, Stuttgart: Deutsche Verlags-Anstalt, 1967; New York: Praeger, 1968.
[2] Plésums, Guntis, "On Teaching Structure Systems," *Journal of Architectural Education*, Vol. XXVII, No. 4, 1974, pp. 69-76.
[3] Yanagi, Sôetsu, *The Unknown Craftsman*, New York: Kodansha, 1972, p. 194.
[4] Plésums, Guntis, "From Behavior to Meaning: On Teaching Membrane Structures," *The Design Process, Proceedings*, Vol. 1, Orlando: International Symposium on Architectural Fabric Structures, 1984, pp. 157-162.
[5] Ibid., pp. 159-161.
[6] Roland, Conrad, *Frei Otto - Structures*, London: Longman, 1970.

Pencil Towers: VRML as an Investigative Tool

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Editor's note: The full text of this paper was not available at the time of publication.