Visualization Tools:
Learning about Structures with Models

BRUCE LONNMAN
The Chinese University of Hong Kong

INTRODUCTION: STRUCTURES IN ARCHITECTURAL EDUCATION

A fundamental shift in the way structural technology is taught in schools of architecture has emerged in recent years. It was initiated primarily by a growing dissatisfaction with the emphasis on analysis that characterized the approach borrowed from engineering that dominated architectural structures teaching up until recently. Now a new approach emphasizing *visualization* and employing traditional techniques such as physical models and graphic statics, as well as new technology in the form of structural modeling software is extending the qualitative approach first introduced by Mario Salvadori[1] nearly forty years ago. The essence of this approach is visualization: observing the response of structure to applied forces; perceiving the interrelationship of material, form, and structure; and seeing the structure in the context of the whole building or assembly. Structural models, both physical and digital, can play a significant role in helping us to better visualize structure in each of these three areas.

The limitations of an engineering based instruction in structures for architects have been recognized for some time[2]. Attempts to condense the vast amount of content typical of a program for structural engineers into a few courses in an architectural curriculum usually results in an over-simplified introduction restricted to the study of a few basic elements and limited to the analysis of isostatic systems. The shortcomings of such an approach should be evident; the content is not rigorous enough to produce capable structural designers nor is it general enough to provide architects with the broad knowledge of structural systems and their basic characteristics that they need. Instead a compromise situation often prevails in which students of architecture learn to design a few select members to meet code (generally beams, columns, and concrete slabs) but lack the deeper understanding of structural behavior that would enable them to use structure as a creative design medium in shaping and influencing architectural form.

STRUCTURAL MODEL TYPES

The term "model" can have several meanings. It can be a small scale representation of something (real or imagined), a prototype, an analogy used to help visualize something, or even a system of postulates and inferences based on a theory which explains a natural phenomenon. The first three of these definitions describe models that are frequently used to explain or understand architectural structures. Probably the most common is the small-scale representation model. This can be either a purely representational or *form* model created for the purpose of studying the geometry, shape, or configuration of a structure, or a small-scale *behavior* model, which is used to study the response of a structure under load. Structural models which behave like the actual structure they represent (i.e. loads, stresses, strains, and deformations are related) are called *direct models. Elastic models* and *strength models are* two types of small scale, direct structural models.

A full-scale *prototype* model is sometimes created to test a new structure before it is used in an actual building. For example, the construction of a single vaulting bay of a Gothic cathedral to test for stability can be viewed as an early prototype model. In the late 1840's, several crescent trusses of the famous Lime Street Station in Liverpool were built as prototypes and load tested to assure their adequacy[3]. In research the testing of full-scale structural prototypes usually precedes the codification of design guidelines. For example, the first building codes for reinforced concrete developed in Germany and Switzerland around 1902 were based on laboratory structural testing of full-scale concrete elements at the beginning of the century.

The third type of model is the *analog* model. It is based on analogy, that is, on a comparison that uses a resemblance between two things, which are otherwise unlike each other. Analogue models have sometimes been used in the past to explain a new concept. One of the more famous examples is Giovanni Poleni's inverted hanging chain analogy in a report of 1748 to explain the shape of a funicular arch.[4] In the teaching of basic structures many instructors frequently use analogue models to describe various concepts. For example, the use of a flat steel ruler to illustrate the different resistances to buckling in the X and Y directions of a column is a demonstration using an analog model.

Of the different types of structural models, an obvious distinction is made between *physical* and *digital* models. Physical models are scaled representations of a structure or component, constructed of materials that may or may not be the same as in the actual structure. Before the development of computer modeling, physical models made important contributions in research, design, and education. But the construction and testing of physical models is costly and with advancements in computer software, digital models, which are generally less expensive, have supplanted most types of physical models in research and design.[5] In teaching, however, physical models remain effective and continue to offer some advantages over digital models, such as their tactile presence and three dimensional form.

Strictly speaking, in engineering a structural model is "a structural element or assembly of structural elements built to a *reduced scale....* which is to be tested, and for which *laws of similitude* must be employed to interpret test results."[6] This definition of a model applies mainly to research and design models, which are created to either, determine or confirm the structural performance of a system. With a structural scale model, the structural behavior or performance under loading of a full size structure can be determined directly by the measurement of deformation and strain in the smaller model. The reduced scale model must be geometrically similar in every aspect to the actual design and applied loads must be representative of the actual loads predicted for the structure. Also differences in scale and material between the model and prototype must be taken into account by employing similitude or scaling relationships.

PHYSICAL MODELS IN ARCHITECTURAL EDUCATION

Behavior Models

The role of structural models in education is somewhat different from that of research or design practice. The objective of the latter is usually to predict the performance and failure capacity of existing or proposed structures. These models must be developed and tested scientifically to insure the validity and precision of the data obtained from measurement. Structural testing labs with large load application machines sophisticated measuring devices and skilled technicians are required. In education, however, models serve primarily as instructional aids, and for this use their precision is less critical and the complexity of the structure being modeled is typically of a lower order. While it may be useful on occasion to measure stresses and deflections, a more important objective in a teaching model is the visualization of structural behavior. For this purpose, models which exaggerate their response to loads are usually better suited since structural deflections are typically of such a small order of magnitude that they are seldom visible in the normal range of loading.

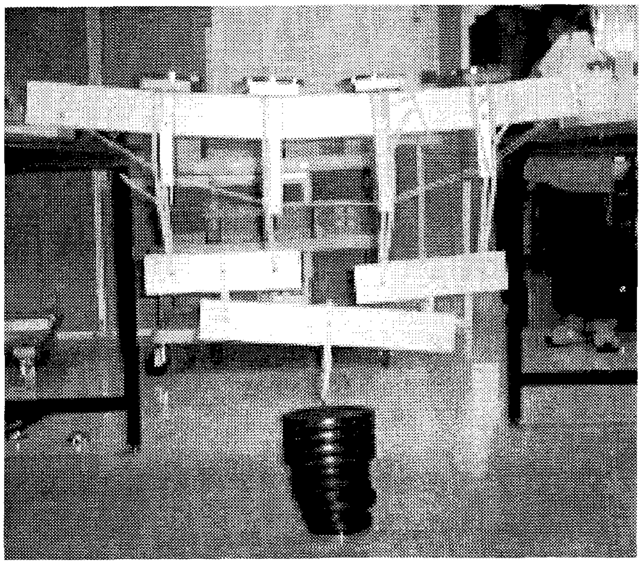


Fig. 1. Composite psf beam model under loading.

There are basically two ways to produce exaggerated deflections in demonstration models. One can either reduce the moment of inertia of a member by making the section small relative to the member length or else use a more flexible material (i.e. low modulus of elasticity) for the structure. To illustrate certain behaviors such as beam deflection or frame bending, it is often easiest to reduce the cross section of the member. This produces large displacements making the deflected shape clearly visible. An unavoidable drawback, however, is that changing the proportions of member sections distorts the appearance of the structure, causing the model to lose its resemblance to the real thing. A simple beam bending demo whose purpose is to verify the deflection formula, might use a wood 'beam' of cross section 1 cm x 2 cm supported on points 1.5 meters apart. In this case the depth to span ratio is 1:75 (compared to a normal ratio of 1:20) insuring visible and measurable deflection. In a similar manner, a two-dimensional frame model constructed of thin cardboard planes for the beams and columns bears only diagrammatic resemblance to a real structural frame. However, the flexibility of the members causes large deformations helping to make visible the inflected shape, the rotation of rigid joints, and the position of points where the curvature reverses.

The alternative is to use an elastic material with a low modulus of elasticity. Lightweight, polystyrene foam (insulation board material) is a common, inexpensive material, that has a low E value of about 1000 psi. This feature, combined with the ease with which it can be cut and shaped, makes it an ideal material for creating structural behavior demonstration models[7]. For example, a series of solid rectangular beams of different proportions cut from a sheet of polystyrene foam (psf) can effectively illustrate the relationships between sectional shape, profile, bending, and deflection. Alternatively, pieces of psf can be glued and/or assembled together to create shapes and configurations that dramatically illustrate more complex structural behaviors, such as column bucking, plate shear, folded plate rigidity, and many more.

Form Models

In addition to using models to observe structural actions or behavior, it is revealing to look at the *form* of structure in a model. This is especially helpful in buildings where the system of support lies hidden within the construction or is obscured by other building systems. By isolating the structure from its context, a reduced scale form model reveals the shape and configuration of the structure, helping us by visual means alone to understand the logic of its design. The form model can also serve as an excellent three-dimensional diagram for studying the geometry, scale, and load path of a structural system.

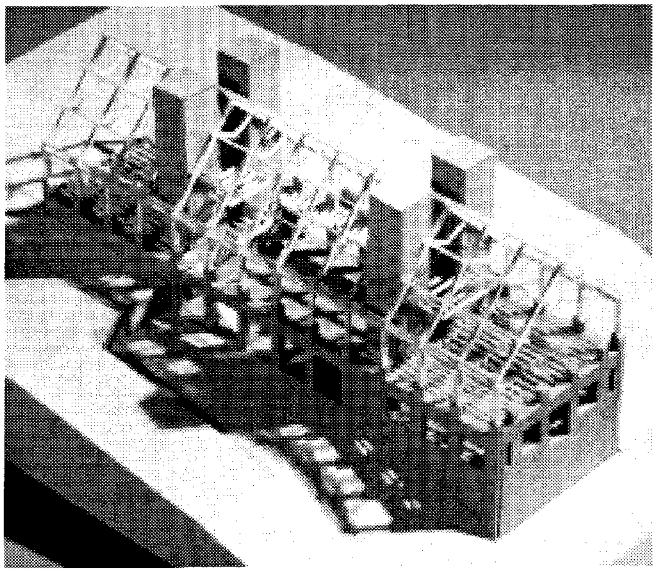


Fig. 2. Student project with structural frame revealed.

Formal models of this type, which unveil the structural scheme of a design proposal or historical precedent are of particular value to architects, for whom pictorial visualization (versus mathematical formulae) is the normative language of design. The work of Heinrich Engel in this respect is compelling.[8] In his book, *Structure Systems*, Engel examines by graphic means alone the morphology of structural systems. Line drawings and photographs of structural form models illustrate the diversity and limitless variation of the basic structural types.

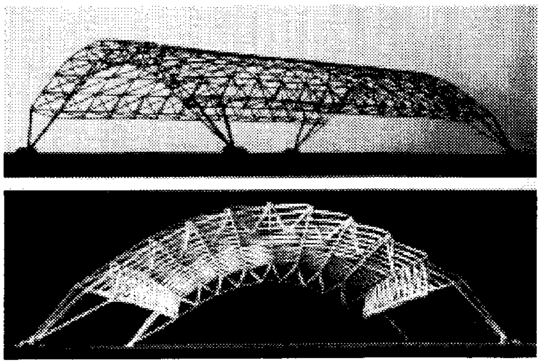


Fig. 3 Illustration from Engel: Truss Vault Model.

Diagrammatic line drawings explain the structural behavior of each type, showing load path, deflected shape, and member force diagrams. Of all the different approaches attempted since Salvadori, Engel's work perhaps comes closest to the goal of explaining structural concepts in a qualitative manner without the use of mathematics and physics, yet also without limiting the discussion to only the most simplistic structures.

In the past models depicting only structural form have been created to explain the structure or construction system of important projects to a client, builder, or the public at large. The well known framing model of H.U.Grubenmann's Schaffhausen bridge of 1758 illustrates the complex layering of strut, beam, and arch that comprises the structure. Interestingly, some of the first load capacity model tests were performed on reduced scale wooden models of proposed bridges of the same type as Grubenmann's, designed just a few years later (1766).[9] Although a lack of knowledge concerning similitude requirements between the actual size and the scale model caused the results to be misinterpreted, the attempt to use models to determine the safe load capacity may be among the earliest such examples.

Sometimes a structural form model can be created as part of a studio research and documentation phase and then used throughout the duration of a design project as a structure precedent or standard. In a design studio exploring vernacular architecture in China, a model of a timber frame of the type found in the Yunnan Province served as a construction reference model for a contextually oriented design problem. The frame model was a 1:20 scale reproduction of an actual house frame under construction and measured by students during a field trip in China.

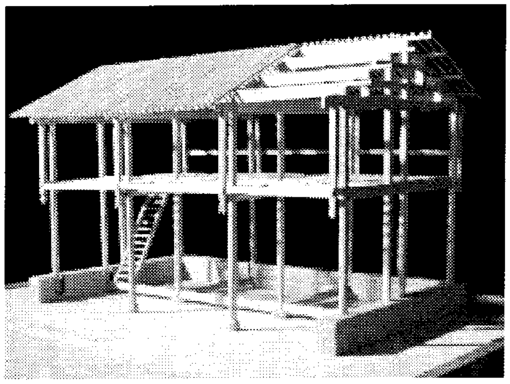


Fig. 4. Model of a Chinese timber frame.

In addition to the overall frame, attention was paid to some of the details, in particular to the critical joinery conditions. Several traditional timber connections were modeled at a scale of 1:5 and were useful in understanding the construction principles.

Finally an important category of physical models useful in design teaching is the prototype model. The term "prototype" generally refers to "a first full-scaled and usually functional form of a new design"[10]. R. Buckminster Fuller's first geodesic dome assembled in 1948 at Black Mountain, North Carolina was a prototype. Previous to this, Fuller explored the geometric form of the geodesic dome in small-scale study models made of paper and cardboard. True-size and actual materials combined with an investigation of a new form or application distinguishes a prototype model from other types of physical model studies.

Today in architectural education there is a renewed interest in the "hands on" construction studio. Full-scale, design-build projects are being introduced in some schools as a means to integrate construction and design.[11] Most design-build exercises of this type adopt a program for a small building or pavilion, which becomes the focus of a team collaboration involving all aspects of the project, from concept to built form. The principal drawbacks of this approach are the size and complexity of the design problem (real building projects involve a scope much broader than a typical studio project), the length of time required for completion (often exceeding a full term), and the cost of materials, tools, and transportation. An alternative, scaled-down approach might achieve the same benefits of construction experience and knowledge of the building process without the organizational and technical difficulties of producing a small building.

A studio project entitled "lessRoof" illustrates such an approach. In this exercise, students from years 1 - 3 formed teams to design and construct a small wood structure in a period of about a week. To accomplish this goal the project had to adopt certain parameters to minimize size, cost, and scope. As the title suggests, the project entailed the design and testing of a small, lightweight roof structure prototype.[12] With a given span, a required load, and a kit of lightweight materials for construction, each team accomplished the design objectives, from concept to full scale construction and testing on schedule. This successful outcome was strongly influenced by three key considerations: i) the limitations on size, envelope, materials, etc. imposed by the program; ii) a carefully organized schedule with set deadlines for the various phases of work; and iii) the requirement that the design be built only with the use of hand tools. At the end of the week each team presented their design and tested its load capacity on a specially made support frame.

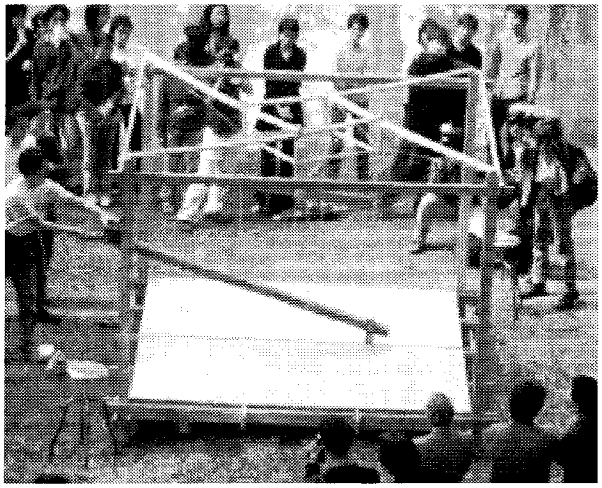


Fig. 5 Load test of a lessRoof project.

Interactive Models

In general, visualization models fall into two groups: demonstration and interactive. Demonstration models have a long history in teaching. They are carefully designed setups that isolate specific structural behaviors to explain and perhaps dramatize a principle to a group of students. Interactive models engage the user and allow for the discovery of structural principles through individual play and problem solving. A physical model of a building frame that lets the user modify the joints and support conditions and then see the effect on deflection is an example of an interactive model. Computer models, because of the ease with which they can be altered, encourage interaction with the user. Various forms of digital models and their use in teaching structures are discussed in the next section.

In summary, listed below are some types of physical structural models and their uses:

I. Form model	Visualization of a structure in design. Testing a construction operation or sequence. Serving as a 3-D visual aid for new construction. Serving as a 3-D visual aid for educational purposes.
II. Behavior model	Demonstration of a structural action (e.g. buckling). Validation of a structural principle or relationship (e.g. bending stress formula). Measurement of strain & deflection for prediction of elastic behavior in the actual structure. Determination of ultimate load capacity.
III. Analog model	Explaining a structural concept in a design. Explaining a structural concept in teaching.

DIGITAL MODELING

While physical models have long been recognized for their potential as teaching aides, the use of computer or digital models for the purpose of understanding or explaining structural behavior is relatively new. Since the 1950s, when the significance of computers for structural analysis first became evident, there has been a steady development in the methods used to harness the speed and numerical processing capabilities of the computer. Today, finite element analysis and graphic displays have enabled structural analysis software to become more accessible than ever. It is not uncommon for non-specialist users (e.g. architects and architectural students) to model and analyze a structure in minutes that might have taken experts hours, if not days, to do just a few decades ago. Of course, an obvious danger exists if the user lacks the experience to judge whether performance values obtained are either approximately correct or invalid by orders of magnitude. The problem, known as the "black box syndrome", has led to reluctance on the part of many instructors to introduce computer aided analysis in structures teaching before the student has acquired an understanding or "intuitive feeling" for structural behavior through traditional means.

Digital computer analysis should be supplemented by other methods of evaluating structural behavior, such as by approximate hand calculation or physical modeling. A good structural designer will know before performing a detailed computer analysis what the outcome is likely to be. By analogy, one might say that the computer is more like a pair of glasses; sharpening the vision as opposed to giving eyesight to the blind. An informed intuition for structure should always accompany the precision of a digital analysis. It is also important to see the computer not simply as a tool for making analysis easier (or possible, as in the case of indeterminate structures) but rather as a new instrument for discovery.[13] In this sense the computer may be used as a device to reveal new information and thus encourage the exploration of structure in new ways. For the computer does possess enormous potential to enhance our understanding of the behavior of both simple and complex structural systems.

There are two distinct roles for computer modeling and analysis of structures in design education. First, as a means for revealing the structural behavior of systems, subsystems or individual elements in order to develop an understanding of the basic principles of structures. And second, as a design tool to assist in the preliminary development of a structural design. Both procedures involve a reiterative, trial and error process that the computer is ideally suited to accommodate.

Current structural modeling software such as Multiframe® (a product of Formation Design Systems Ltd.) combines the familiar commands and menus of standard architectural modeling software with the particular attributes of a structural model (nodes, elements, applied external force, nodal restraints, and section properties). Information entered by either mouse or key, defines a structural model the computer can analyze for a particular load-case or combination of load cases. This analysis takes only seconds, after which a range of graphic representations of the model's structural behavior is available. Most useful are force (axial, shear, and moment) and deflected shape diagrams overlaid on the structural model. It is this aspect of enhanced visualization of performance, together with the ease by which the parameters of the structural model (geometry, member section properties, connections, supports, loads, etc.) can be altered that qualifies digital modeling as a powerful teaching tool.

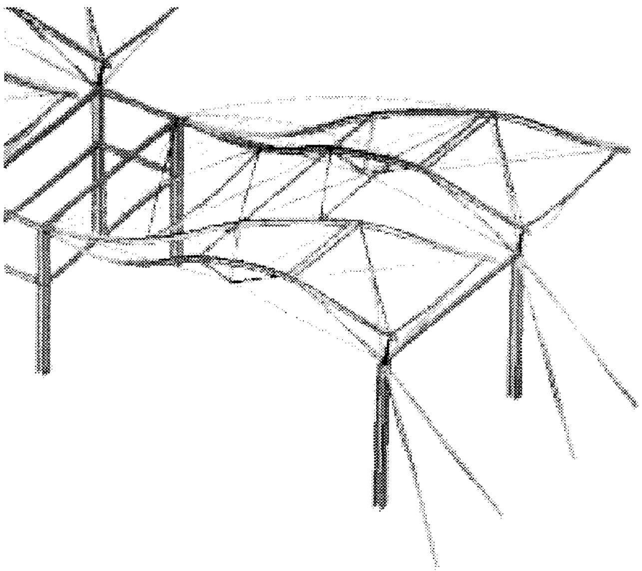


Fig. 6. Student analysis project: Thomson factory by R. Piano.

Architecture students traditionally encounter difficulty with those aspects of structure that involve quantification of forces and their resulting effects on a structure. In particular, the construction of internal shear and bending moment diagrams is an especially hard technique for non-technically trained students to learn. The insight that can be gained from such a diagram however, tends to keep it in the syllabi of most courses on structures. Fortunately, the standard graphic display of most current structural software includes this important visualization. Thus the time saved by using the computer to solve and create these diagrams can be put to better use examining the response of the structure to a variety of alternative design configurations, member connection types, support conditions, and load cases. Most importantly, digital modeling provides the non-specialist user with a tool that can be used to study indeterminate structures of higher orders of redundancy than was previously possible, even by the most capable engineers. And as many designers are aware, the majority of structures that we design today are indeterminate.

Numerical Validation and Calculation

The debate concerning the role of mathematics and calculations for teaching structures in architectural education still continues. There is little doubt that some mathematics, particularly algebra, geometry, and trigonometry, is useful and important in understanding structural concepts. Salvadori emphasized this point saying: "Structures are best presented in the language proper to the quantitative analysis of measurable phenomena: mathematics; not the complex mathematics required for an understanding of the more advanced aspects of science, but the simple mathematics of arithmetic and algebra, and, sometimes, elementary calculus."[14] While the professional engineer must use calculations to predict the behavior of structures and quantify the results for the purpose of selecting appropriate structural members, the beginning architecture student will use numbers as a means towards understanding structural behavior. The calculations themselves are just a tool. But they are necessary to validate mathematically and *quantify* the relationships between different variables in a structural equation. Again, Salvadori: "No thorough knowledge of structures may be acquired without the use of....mathematical tools. Mathematics does not explain physical behavior; it just describes it."[15]

As an example, consider a typical statics problem in a beginning structures class. The objective is to determine the shear and bending moment diagrams for a beam subjected to certain loads. The real goal however, is to gain insight into how the beam actually behaves, that is, how does it carry load across a span and what effect on its shape does this action have. Typically, the student begins by sketching the deflected shape of the structure based purely on intuition. To confirm the assumption of beam deflection, some calculations are required. Using principles of equilibrium and various geometric relationships, first a shear and then a bending moment diagram is "plotted" along the length of the beam. Done by hand, this operation takes time and requires numerous calculations. Unfortunately the calculations often become the central focus and obscure the real objective of the assignment, to understand how a beam reacts to different loads and to visualize its deflected shape.

For this type of exercise the computer is a remarkable tool. With access to software such as Multiframe®, the analysis and graphic representation of member forces is accomplished in minutes. Alternate load cases are easily compared and different support conditions or member properties (to observe the effect on deflection, for instance) are studied in quick succession. Substitutions and comparison of alternatives such as this exercise suggests, demonstrate the potential of digital modeling and one way that it can be used in structural teaching. Again, the numbers and the graphic results do not *explain* structure, they merely describe the behavior analytically, from which conclusions can be drawn.

Interactive Digital Models

Another interesting method of using the computer in structures teaching is through the use of interactive models. An interactive computer model is one that provides the user with some means to affect the response of the digital model, ideally in a simultaneous manner. Interactive models can be created to demonstrate particular structural concepts making use of the instantaneous visual graphics of the computer. For teaching purposes, the interactive model allows students the freedom to access the model on their own time and review it as often as required.

There are many different ways to create interactive structural models. Using Flash® software, for example, animations displaying structural behaviors can be created. An interesting project developed by Luebkeman used JAVA to create a few interactive programs known as "Applets" which are downloadable through the Web from a central location (for example, a network server) to a user's personal computer.[16] Each applet focused on demonstrating a particular structural behavior. For example, one case used an interactive model of an ultra-slim high-rise known as a "pencil tower", subject to variable wind loads, which induce lateral deflections and base shears of varying magnitude. The adjustable parameters of tower height, width, and magnitude of applied wind load can be modified, and the computer quickly computes the shear, moment, and deflection curves and displays them in scale with the elevation of the tower. The user simply adjusts the parameters with the mouse and instantly obtains a screen visualization of the wind effects.

Structural Analysis and Studio Design Work

The use of computer structural analysis can also contribute to student design work under certain conditions. Generally it is not of much interest for students in design to "engineer" their projects using structural design software. The process of structural design in the professional sense is too specialized for architects to find very useful. However, this does not preclude the use of computer analysis and digital modeling for all design studies. There exist many opportunities in studio work where structural analysis, using the computer, can be an effective way to study relationships of structure and form.

For illustration consider a beginning level studio project for a small gymnasium. This problem is developed to focus the student's design exploration on the development of a steel roof structure. This is a type of problem that examines layered roof construction, steel framing, lateral stability and a range of specific technical issues. The dominant visual design feature is the space of the gym, with its exposed long span structure. In the conceptual phase of the project, students begin with traditional form model studies examining the structural system type, its pattern and overall appearance.

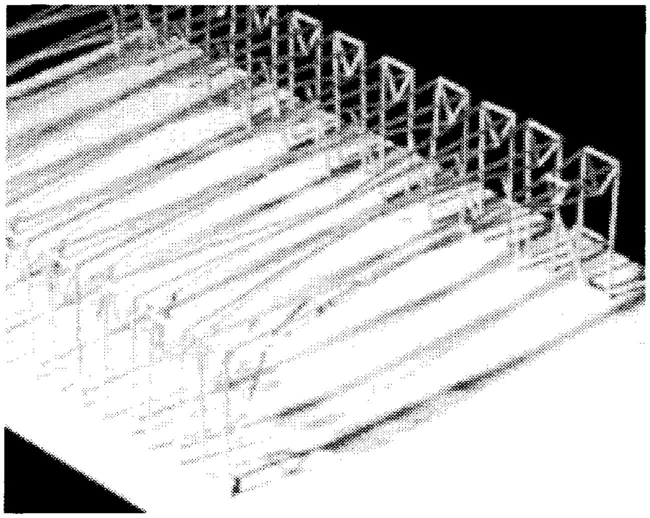
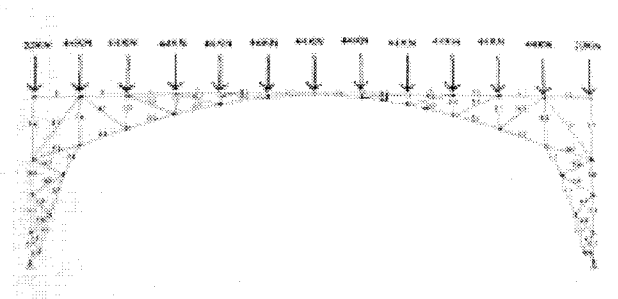
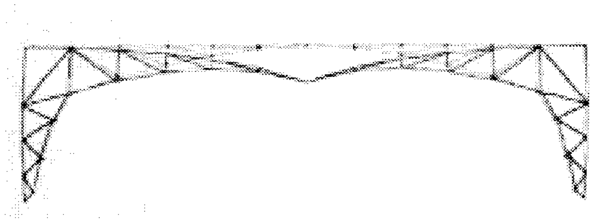


Fig. 7. Structural system configuration study model.

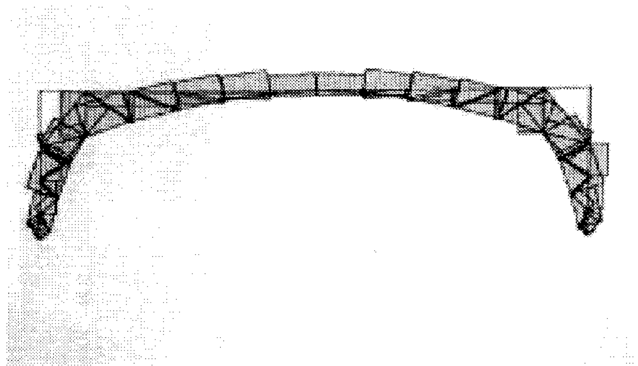
Precedent studies and 'rule of thumb' charts guide decisions pertaining to the basic configuration. Once the design reaches a preliminary stage in which the structural concept is clear, a more detailed structural investigation is made to study the structural "correctness" of the form based on assumed loads and initial physical dimensions.



STRUCTURAL MEMBERS



DEFLECTED SHAPE



AXIAL FORCES

Fig. 8. Truss frame digital analysis using Multiframe®.

Depending on the type of system, the analytical tools vary. Arch and simple truss systems may be studied using graphic statics, while more complex and indeterminate systems, such as trussed beams and continuous frames, lend themselves to computer analysis.

Whether graphic statics or computer analysis is selected, it is important to emphasize that the process be reiterative and comparative. In other words, the tools are meant to be used as part of the design process and not as a final check on structural stability or member selection. For this reason the student is encouraged to interpret the results of the analysis and determine how improvement can be made in the design.

While most architectural design students can perform basic calculations on simple, determinate structures (e.g. a pin connected truss, a three-hinged arch), few students have the ability to examine in detail the kinds of structures that student design projects most frequently adopt. For example, a very popular and increasingly common structure is the trussed beam. This is a spanning structure that is neither a beam nor a truss, and cannot be analyzed as such. It is an example of an indeterminate system whose behavior is conditioned by the relative stiffness and strength of each component. With computer aided analysis, a design student can explore the effects of various parameters and begin to understand the relationships between the form of the structure (its configuration, member sizes, and connections) and its behavior under load (how it will deflect, what portions will be stressed the most, etc.). In so doing a more efficient spanning structure can be created; one whose apparent beauty might derive from the correct proportioning of the elements as much as from the choice of the structural type.

CONCLUSION

This paper has briefly outlined some of the types of models, both physical and digital, that are currently used in architectural education. While certain models are mainly useful for explaining structural concepts and find their place in the lecture or lab demonstration class, others are appropriate for use in studio, as visualization tools aiding the design process. How these new tools or techniques can more effectively support structural investigations in design studio remains an interesting question requiring much more experimentation and trial. This approach to teaching structures, however, characterized by a greater emphasis on the visualization of form and behavior, will continue to evolve and influence architectural education in the years to come.

NOTES

[1] Mario Salvadori and Robert Heller, *Structure in Architecture*, Prentice-Hall, NY, 1963.

[2] Heinrich Engel, "Perspective: Dilemma of architectural education", in Gulzar Haider (ed.), *Structures and Architectural Education: In Search of Directions*, Ottowa, Ontario, Architecture Publications, 1974, pp.93-98. Proceedings of a Workshop held at Carleton University, Ottawa, May 1972. The contribution of Heinrich Engel is especially clear in distinguishing the differences between engineering and architectural approaches to the teaching of structures.

[3] R.J.M. Sutherland, "The birth of stress: a historical review" in *The Art and Practice of Structural Design,* London, The Institution of Structural Engineers, 1984, pp. 11-12.

[4] Hans Straub, *A History of Civil Engineering*, London, Lenard Hill Limited, 1952, pp. 140-43. Straub refers to the work by Giovanni Poleni, *Memorie istoriche della Gran cupola del Tempio Vaticano*, 1748.

[6] Harry G. Harris and Gajanan M. Sabnis, *Structural Modeling and Experimental Techniques*, Boca Raton, CRC Press, 1999, p..2.

[7] Richard E. Kellogg, *Demonstrating Structural Behavior with simple models*, 1994. Professor Kellogg has developed the technique of polystyrene foam modeling with hotwire and glue gun. By very simple means he shows a great variety of models demonstrating nearly every important structural behavior.

[8] Heinrich Engel, *Structure Systems*, London, Iliffe Books, 1968.

[9] Hans H. Hauri, "Thoughts on the historical development of methods for dimensioning bridges" in Tom Peters (ed), *The Development of Long-span Bridge Building,* Zurich, ETH Zurich, 1979, pp. 153-157.

[10] Merriam-Webster Online, Merriam-Webster, Inc. 2000, Springfield MA.

[11] William J. Carpenter, *Learning by Building*, New York, Van Nostrand, 1997.

[12] Bruce Lonnman, "Constructed Designs" in Edward Allen (ed), *Connector,* Vol. VIII, Number 1, (Spring, 1999): pp.1-3. An account of the design-build project called "lessRoof".

[13] R. Gary Black and Stephen Duff, "A Model for Teaching Structures," *Journal of Architectural Education*, 48, 1 (September, 1994): 38-55. In one of the first major articles to explore this problem, Black and Duff describe an approach that embraces computer modeling and uses finite element analysis for the teaching of structures in architecture.

[14] Salvadori, *Structure in Architecture*, p. 450.

[15] Salvadori, *Structure in Architecture*, p. 452.

[16] Chris Luebkeman, "JAVA Applets: Web-based Interactive Visualization Tools to Enhance the Effectiveness of Teaching / Learning of Architectonics" in *Proceedings: 85th ACSA Annual Meeting*, Washington, DC, 1997.