Teaching Statics as a Creative Discipline

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To us it is self-evident that the purpose of teaching the subject of structures is to enable students to create structures, not merely to evaluate them numerically.

We reject the common assertion that students should not be encouraged to create structures until they have taken a series of courses in structural calculations. We believe that students should be involved in designing structures in the fullest sense from their first days as students of statics, throughout all their years of study of architecture. Along the way, the fundamentals of structural knowledge may be introduced by the teacher as they are needed to enable the students to carry out their design work. Thus creative work furnishes both a motivation for learning the fundamentals of structural behavior, and ongoing projects to which the developing fundamental knowledge may be immediately applied.

The basic knowledge that students acquire within the first few days of an ordinary class in statics is sufficient for them to undertake the design of funicular structures and trusses. This catapults them immediately into the exciting realm of longspan structures where, to their surprise, they find themselves able to operate intelligently and effectively as designers and analysts. The thorough familiarity with hanging cables, arches, and trusses that they gain through this experience is the best possible basis for the subsequent study of strength of materials. Beam behavior, for example, is easily understood by a student who is fully familiar with truss behavior and who is able to grasp through a knowledge of cables and arches the significance of the curving trajectories of tension and compression inside a prismatic beam. This student will also understand intuitively that a beam whose longitudinal profile is shaped to resemble its moment diagram will perform very efficiently, and that it will experience no internal shear action under the loading for which it is shaped.

A GRAPHICAL/NUMERICAL APPROACH TO STRUCTURAL SYNTHESIS

To facilitate student design work in the realm of longspan structures, the authors have adapted, modernized, and in some cases invented a closely-related group of graphical techniques for finding form and forces for trusses, cable-stayed structures, funicular arches and shells, and hanging cables.' These serve to make structural actions visible, understandable, and above all, a basis for creating appropriate structural form. Our experience has been that students learn these techniques easily and use them readily and enthusiastically in their design work. Through the simplicity, transparency, and extraordinary power of graphical methods, even beginning students are able to create longspan structures that are appropriate, efficient, and in a surprising proportion of cases, elegant.

Numerical techniques are not neglectedin our approach. A combination of numerical and graphical techniques is advocated and taught, using each to support and amplify the other. Students learn the numerical analysis of trusses and numerical methods for shaping and analyzing arches and hanging cables. But the graphical techniques, which arrive at the same results, are the key to facilitating student understanding and creativity. All numerical methods in structural analysis are based on geometrical diagrams. In many types of structural design operations, especially those relating to the origination and optimization of structural forms, it is most appropriate and fruitful to work with the geometrical diagrams rather than their numerical translations. A substantial proportion of the extant structures that we admire most, such as Maillart's bridges and Eiffel's tower and viaducts, were created primarily through graphical methods.

Our approach includes from the first days of the study of statics some aspects of structural design that usually have been absent from the architectural structures curriculum, especially at the beginning. One such aspect is the study of simple techniques for optimization of the forms and depth-to-span ratios of trusses, arches, and cable structures. Another is the consideration of materials, detailing, fabrication, and erection procedures as normal parts of the structural design process. Many students become particularly motivated as they work on details and construction procedures, perhaps because for the first time they see themselves acquiring the ability to translate their ideas into actual buildings. We also introduce the student to the culture and history of structural design, including discussions of the world's great structures

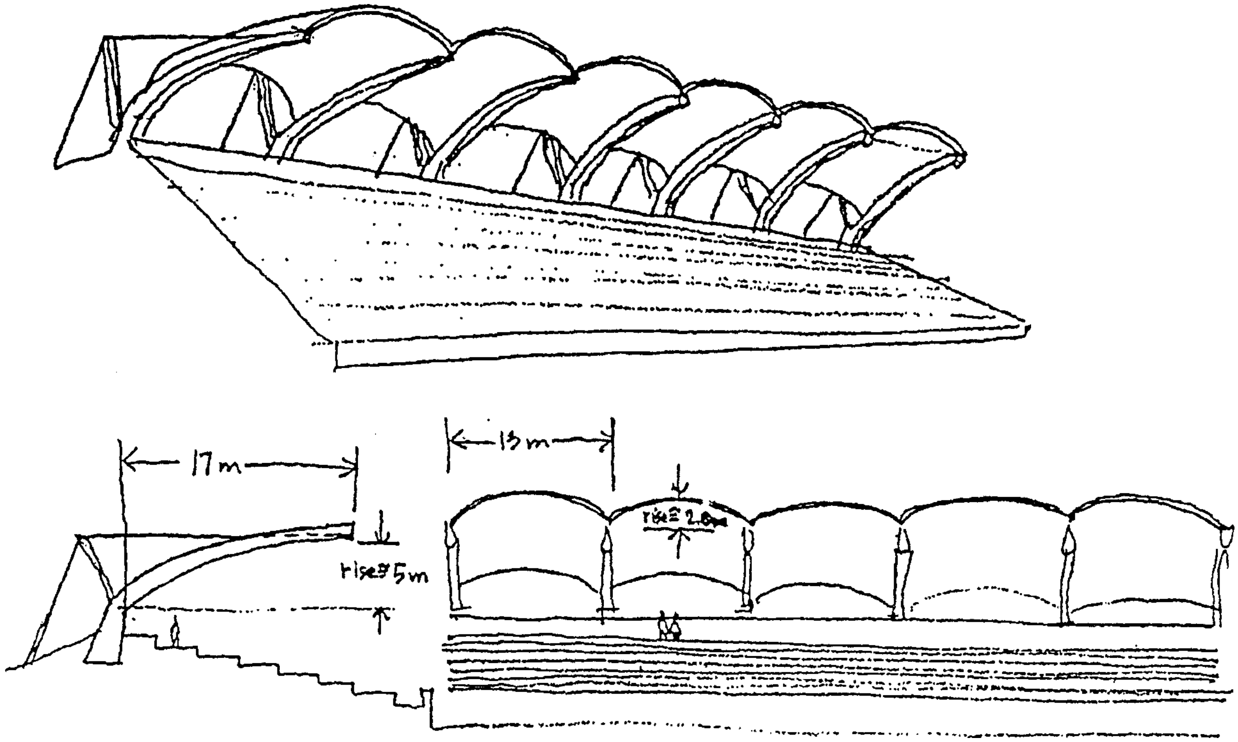

Fig. 1.

and their engineers and architects. We do not merely show and express admiration for the great structures: The graphical tools enable us also to analyze them simply and directly, demonstrating how their forms were derived and how they work. This enables students to emulate the processes by which the great structures were designed. Our approach enthusiastically embraces questions of structural aesthetics as being integral to the discussion of structural function and efficiency.

Though our approach is nonstandard, we do not consider it to be radical. We assert that it is in fact a return to the grand tradition of structures teaching in late nineteenth century Europe that was based on the graphical methods developed by Karl Culmann, James Clerk Maxwell, Robert Bow, and Luigi Cremona. This tradition produced in succeeding generations such master designers as Gustave Eiffel, Antoni Gaudí, Robert Maillart, Eduardo Torroja, Pier Luigi Nervi, Riccardo Morandi, Ove Arup, Frei Otto, Christian Menn, Peter Rice, Jorg Schlaich, Michel Virlogeux, and Santiago Calatrava.

The best way to understand our approach to teaching statics is to look first at just one of the many examples that we have developed to demonstrate structural design methods to students, and then examine a few examples of student work that has been done under our direction.

DEMONSTRATION EXAMPLE: A CANTILEVERED CONCRETE SHELL ROOF FOR A STADIUM

Figure I is a first sketch of an idea for a stadium roof. A row

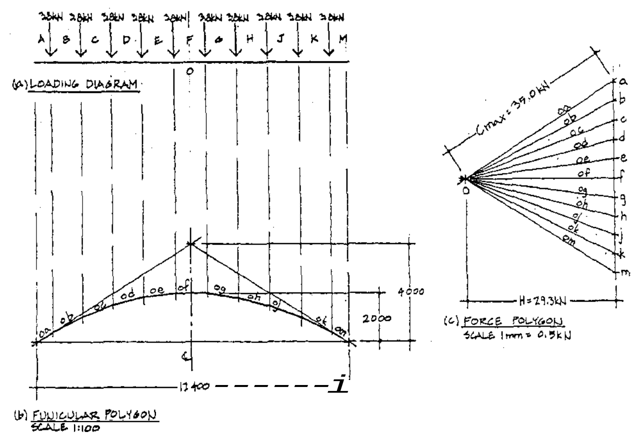

Fig. 2.

of concrete barrel shells is supported by concrete half-arches that are tied back to an inclined strut and thence to the ground. Figure 2 illustrates the finding of form and forces for the barrel shell, based on a uniform distribution of gravity loads. Contained within this figure are all the graphical manipulations from which a funicular form is found for the shell, along with the force in each part of the shell. A parallel numerical derivation, not illustrated here, proves that the graphical results are accurate in this case to within 1% of the numerical values. In Figure 3, a similar construction finds the form of the half-arches, the forces in the arches, and the force in the horizontal backstay under a uniform gravity load. Figure 4 is the graphical construction that finds the forces in the vertical

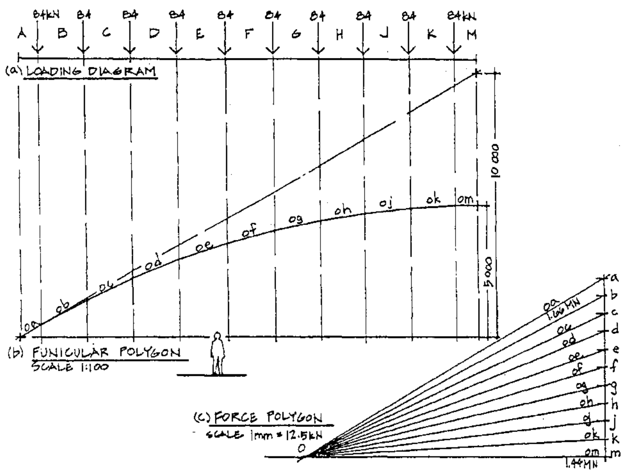

Fig. 3.

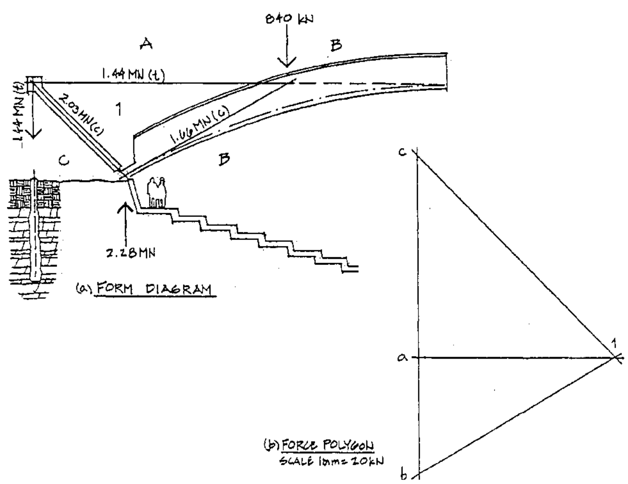

Fig. 4.

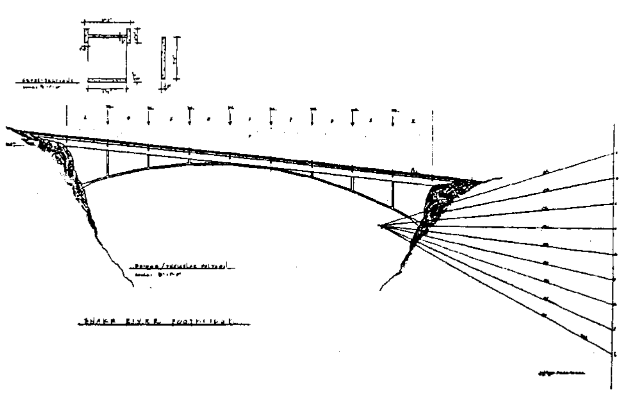

Fig. 5.

stay, inclined strut, and foundations. A comprehensive set of details is developed for this structure; space limitations preclude their illustration here. Procedures for erecting the roof are also discussed. This project is one example of a seemingly complex structure that can be understood and emulated by a student who has a knowledge of the rudiments of statics. Other examples that we take up in similar detail include a wood roof truss, a cable-stayed footbridge, a concrete deck-stiffened arch vehicular bridge, an auditorium with a hanging roof, and a large basketball arena with its roof supported by three-hinged steel truss arches. Numerous smaller examples round out the demonstrations.

STUDENT PROJECTS

The most widely accepted current model of a structures curriculum, statics/strength of materials/wood/steel/concrete, even when it is supplemented by instruction and exercises that develop structural intuition, is grossly deficient in providing students with experience in the creation of appropriate forms for structures. Our approach enables students to synthesize logical, efficient, expressive structural forms even during the first week of a beginning class. We have ourselves pursued this method of teaching largely in design studios, supplemented by weekly or twice-weekly lectures to teach principles and techniques as they are needed. The examples of student work that follow are taken from a ten-week intermediate level design studio taught recently by one of the authors while he was a visiting critic at the University of Oregon.

The footbridge in Figure 5 was designed by Jennifer Freudenberger as a one-week introductory exercise at the beginning of the term. The knowledge needed to find the form and forces for this bridge with its sloping deck was imparted in the 90-minute informal lecture that introduced the studio on the first day of class. The fanlike diagram on the right is a force polygon from which the form of the arch is generated and the forces in the various segments of the arch are determined. The only numerical calculation associated with the design was a P/A computation to convert the 734 kip maximum force in the arch into a first approximation of its cross-sectional area.

The major project for the term was a roof for a covered market. Jean Won's design employs fanlike three-hinged arches made of steel pipes. These were analyzed graphically as trusses. A planned member that radiated to the high point of the roof from the top of the column was shown by this analysis to carry virtually no load and was eliminated. Steel pipe bents in the longitudinal direction of the building provide lateral stability. Ms Won, who had taken no prior classes in statics or structures, also designed the details for her structure that are shown in Figure 6.

Design proposals for this roof by other students included several cable-stayed designs, a suspended roof, assorted trusses, treelike steel umbrellas, precast and sitecast concrete arches and vaults, and several spectacular steel arch solutions, as typified here by the schemes of Vivian Reynolds and Alan Slusarenko, respectively (Figures 7 and 8).

Although most members of this studio had studied structures previously in other classes, largely through numerical analysis, the structural knowledge that was brought to bear on the design problems was largely developed within the studio itself.

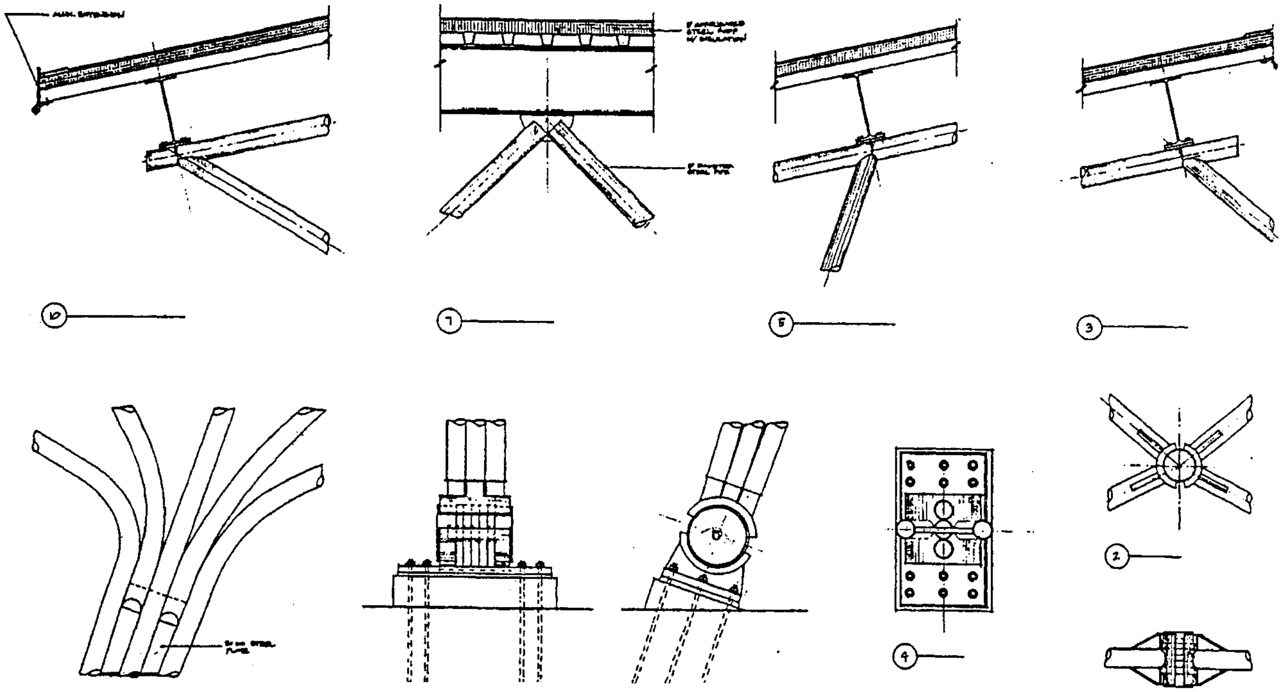

Fig. 6.

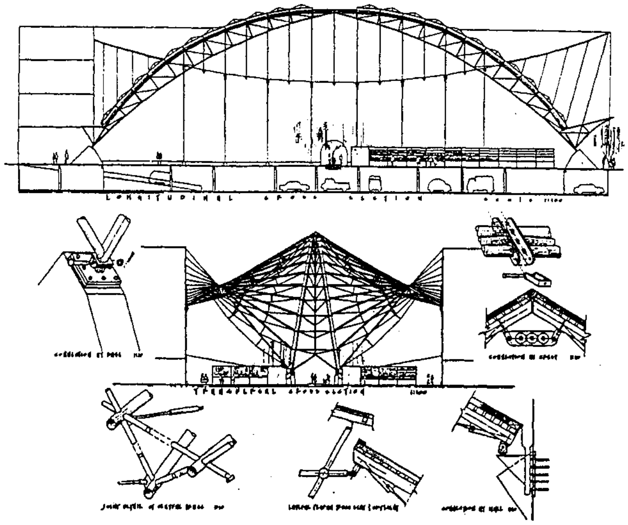

Fig. 7.

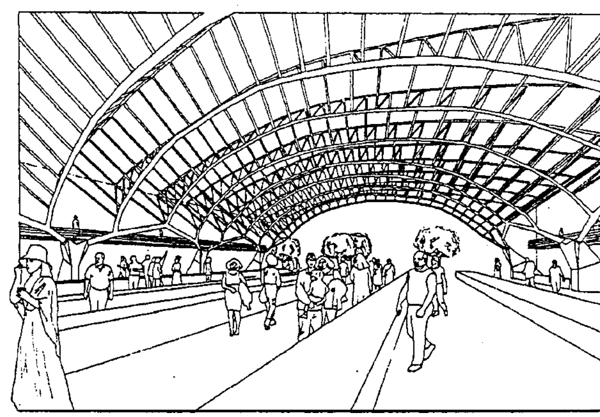

Fig. 8.

CONCLUSIONS

The principles of statics may be learned through students' involvement witheitherthe conventional assortment of small, abstract, purely analytical exercises, or the creative design of original, large-scale,often exciting structures. The authors' experiences indicate that the creative approach, combining as it does both synthetical and analytical activity, is at least equally as effective as the purely analytical one in teaching the principles, and much more effective in starting students briskly along the road to becoming complete, confident designers of structures. The creative approach, especially as it is applied to longspan structures, is also considerably more enjoyable for both students and teachers, engenders an eagerness in students to study structures, and produces abundant presentation material that tends to find its way to the very front pages of student portfolios.

NOTES

[1] Waclaw Zalewski and Edward Allen. *Shaping Structures: Statics* (New York: John Wiley & Sons, 1998).