Teaching by Observation Informs Structure (T.O.I.S.) Digitally Fabricated Models for Structural Education in Architecture

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> The calculation of stresses can only serve to check and to correct the sizes of structural members as conceived and proposed by the intuition of the designer. The work itself is never born from calculation.[1]
>
> Eduardo Torroja

Having taught structural principles to architecture students for over twenty years, I can say, with a certain level of credibility, that one challenge remains constant; how to present highly technical information to an audience that learns primarily through visual means.

Coming to Architecture after completing a degree in structural engineering I was immediately perplexed by my architecture classmates' aversion to anything that required an analytical or mathematical explanation. In my experience this bewilderment is a malady common to many architecture students. Even as we live in an increasingly technological world these students, in general, continue to be intimidated by anything inherently mathematical. Since I also teach structural topics to practicing architectural interns preparing for the Architecture Registration Examination, I am in touch with students from all over North America with varying levels of structural understanding, experience and educational background; and yet they too suffer from this common affliction.

The numeric justification of structural behavior may be the most direct way of teaching structures and is certainly the method by which I, and certainly most of those with engineering backgrounds have been taught, but in my experience it has never been very effective with architecture students and has become increasingly ineffective over the years. I believe that tolerance for this type of traditional numeric instruction and learning is at an all-time low. The challenge *du-jour* is how to teach architectural structures to students who are easily distracted, seek immediate results and seemingly expect to understand through osmosis.

Early in my career, I concluded that teaching an unpopular topic to uninterested students was best achieved by continually injecting my coursework with the latest in presentation technology. While the structural concepts discovered by Newton, Galileo, Euler and others may be timeless, the techniques for communicating those ideas have taken a quantum leap in the last decade. Throughout my career I can identify certain innovations that radically modified my pedagogical approach. One such advance that comes immediately to mind was my switch from a manual SLR camera to a pocket sized digital camera. This new method of recording images energized my approach to lectures by expanding and organizing my exponentially growing visual library. Nearly fifty thousand images later, I cannot identify a structural condition, that I do not have multiple digital images to select from when illustrating my lectures.

As digital software and animation have become a more prominent means by which to represent architecture, students have become facile at manipulating and understanding this new medium. With the help of some highly talented and motivated teaching assistants I was able to once again integrate a new visual technology into my pedagogy. Digital animation has allowed me to offer my students step-by-step depictions of structural frame assembly down to the detail of bolt tightening. These three-dimensional views have become indispensable tools for illustrating a systematic logic of assembly that maintains student interest while conveying critical information.

My latest effort to incorporate technology into the structural education of architecture students prompted me to explore digitally fabricated materials as a means of explaining the behavior of structural members and constructs. The result is a series of digitally fabricated structural models that have fondly become known to us as TOIS (**T**eaching by **O**bservation **I**nforms **S**tructure). The success of this project has again only been possible through collaboration with several very talented students, most notably my co-author on this submission. A former graduate student and now a young colleague, he has firmly established himself as the authority on all things digital at the college. He constantly challenges me to move beyond my cursory knowledge of the technology, so that we may work in tandem. This project has not only been professionally fulfilling, but has also become a mutually beneficial venture, based on our unique "mentor to mentor" exchange.

The TOIS project has involved developing, designing, drawing, and laser-cutting structural models that simulate the behavior of wood, steel, and concrete in a variety of structural systems. It is certainly not unusual for architects and engineers to explore their ideas through building scaled down models or even full size mock-ups to test their concepts. We have all seen the famous black and white photos of Frank Lloyd Wright, Frei Otto, and R. Buckminister Fuller examining models of their structural innovations. The use of digitally fabricated models as presented in this paper, however, is not for the purpose of proposing a novel hypothesis, an innovative structural principle, or any groundbreaking theory. These models are simply intended to communicate basic structural concepts to students, specifically those who begin to struggle as soon as the equilibrium of a beam is expressed in numeric terms. They follow along as the concept is presented until any numbers are assigned to the illustration. Then, as if speaking in mathematical terms is a cue for them to disengage from any discussion of structural stability, they begin to doodle design-investigations in the margins of their grid paper. The TOIS models provide a new tool with which to reinforce the students' inherent understanding of the effect of physical principles on structures and form a bridge to understanding the numeric descriptions of those effects.

The design criteria for the TOIS project was that the resulting educational models had to depict a specific structural condition or system and accurately represent the nature of the material typical for that system, in a scale appropriate for classroom demonstration. The size of these models was immediately established by the limitations of the projection devices, an over-head projector or document camera attached to a digital projector, which would be used to enable everyone in the lecture hall audience to view the models. During a lecture, the models could be "loaded" (pushed in specific

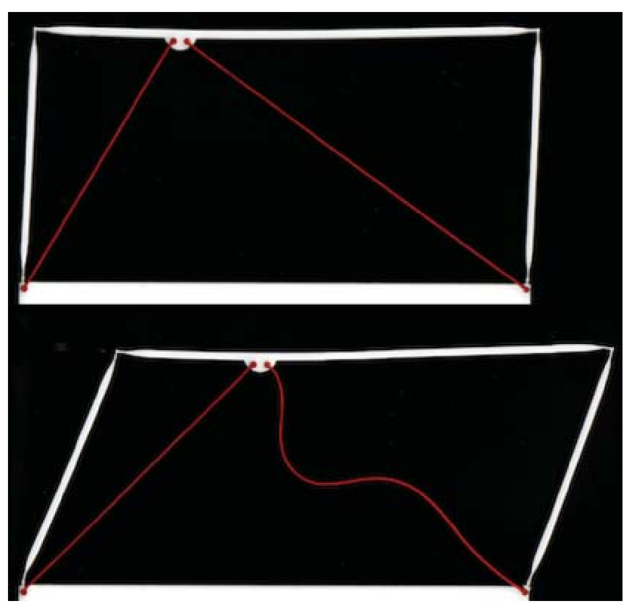

Figure 1. Portal Frame in Unloaded and Loaded Condition

areas) and they would interactively illustrate specific structural behavior. For example, one of the first models fabricated was one that illustrates a slender diagonal brace under compressive loads. By applying force from a certain direction and not from another, buckling may be simulated, thus replicating the performance of a slender steel member in a building subjected to this type of force.

The Universal Laser Systems laser cutter employed in the fabrication of the TOIS has been a vital piece in the overall evolution and success of this project. Digital fabrication equipment of this type allows for a level of precision and repeatability that would not otherwise be possible and has allowed us to work with a unique palette of materials. Considering the small size required for the models, the experimentation has shown that even minute deviations in the intricate details can dramatically alter the overall performance of an individual piece. The consistency of the laser cutter has enabled those details to become driving forces in clearly demonstrating the many interrelated elements of structural dynamics. The impact of this high degree of detail-control can be clearly seen in the development of a functioning pin joint.

Before we were totally adept at utilizing the fabrication technology in this application, we had experimented with the use of purchased mechanical fasteners to simulate pin and roller connections. We soon realized that this off-the-shelf hardware represented an inadequate commitment to the technology and that the materials and fabrication machines available to us were perfectly capable of producing the necessary level of articulation. After numerous iterations we finally designed a configuration that would accurately represent the behavior of a pin connection and satisfy the conditions we had set forth. The result was a horizontal member attached to two vertical members by links whose widths measured merely 8/256 of an inch. This success granted us our first sense of accomplishment, proof of our initial concept, and evidence that the methods at hand would be capable of creating the tools for demonstrating the structural concepts we were striving to explain.

Throughout this project the selection of materials has been a major area of concentration. As a baseline condition the materials were selected to meet a certain level of consistency as well as a high degree of machineability. These criteria left a vast list of materials to be evaluated. The most important criterion for the selection of material, however, became the innate ability of each material to simulate the structural behavior (compression, bending and tension) to be studied in the particular model and its correlation, at scale, to a specific building material (steel, concrete, wood). The current list of materials includes acetal, acrylic, silicone, and spandex. All of these materials have proven to be easily manipulated utilizing the laser cutter, and are uniquely capable of accurately simulating large-scale structural behavior.

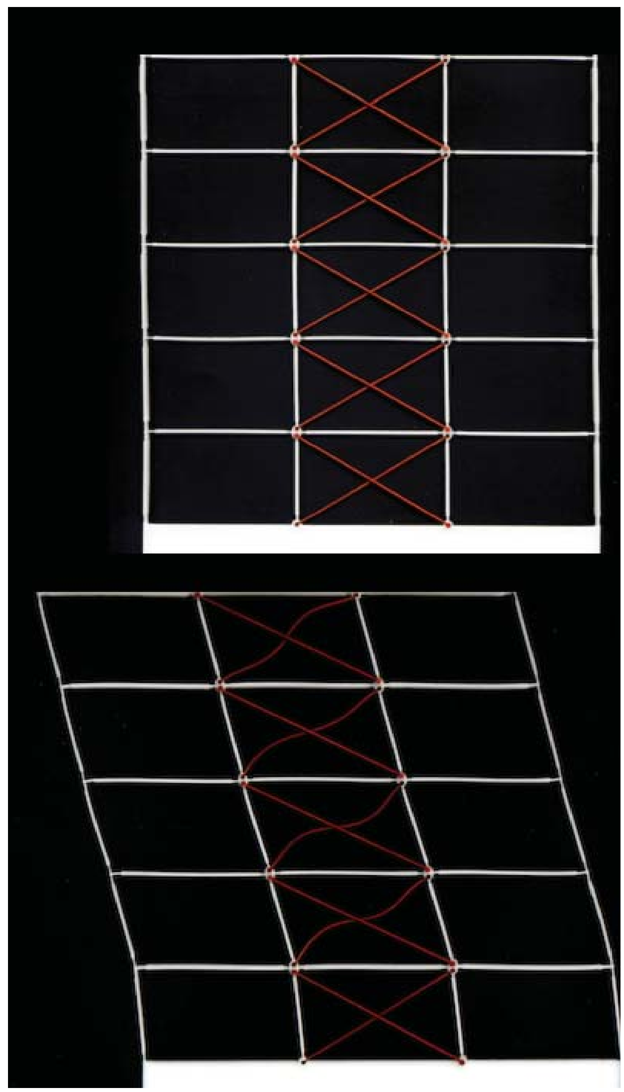

Figure 2. Braced frame studies

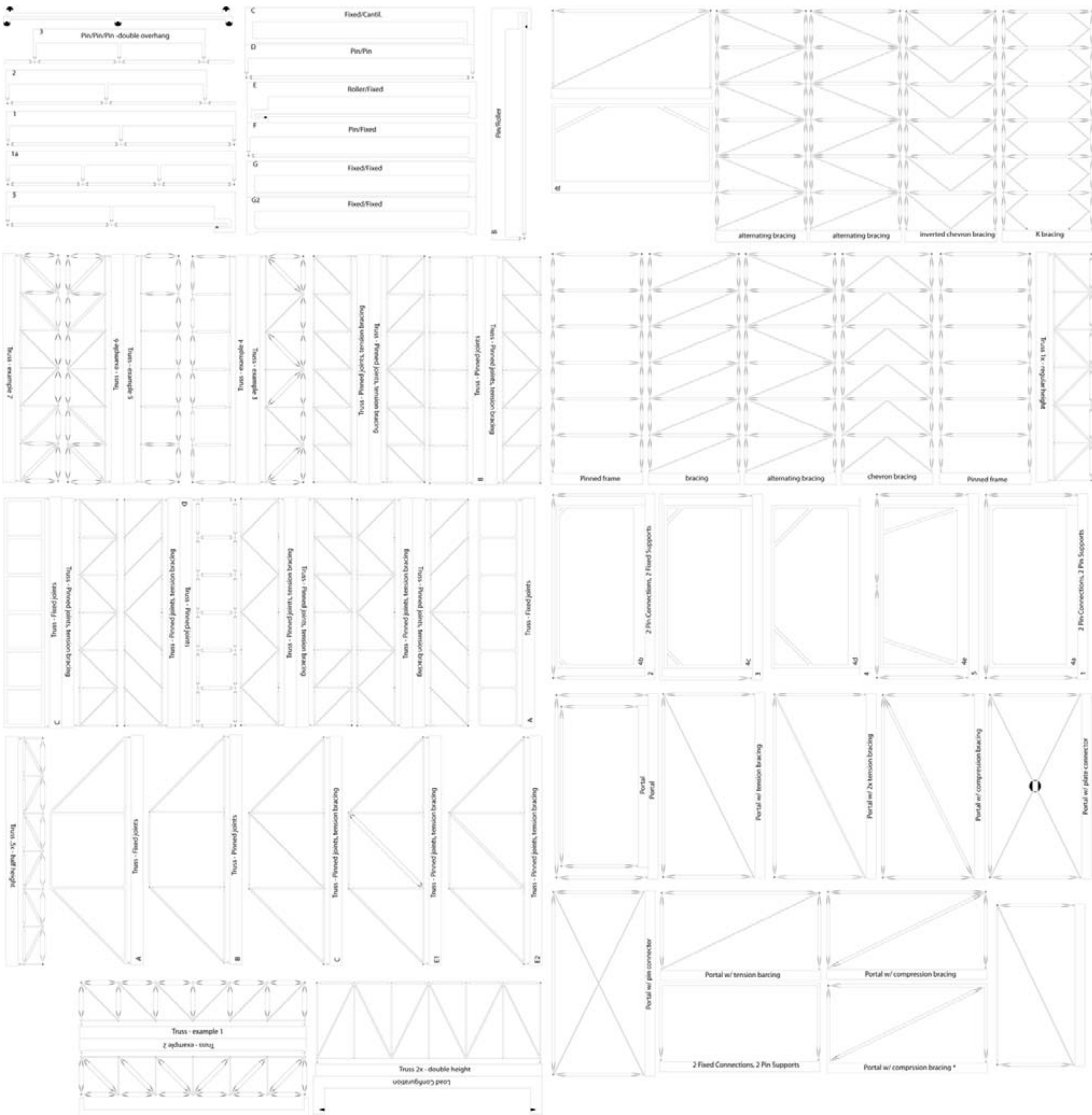

Figure 3. Array of early studies

At the inception of the project the intent was to simulate the behavior of a simple frame structure, specifically a concrete frame. This was easily achieved in acrylic, a material that is relatively strong but extremely brittle. When the acrylic model was subjected to excessive inelastic deflection or drift it was able to mimic the general structural behavior of a full size concrete frame that, by character, has minimal resistance to such strains. The non-ductile nature of acrylic was a perfect analog for concrete as it vividly demonstrated how concrete frames could fail without warning. This demonstration of the loading of a concrete frame was always with the intent of illustrating the potential for collapse through the fracturing of the frame. The acrylic models therefore were intended for a single use only.

The next set of models has been designed to simulate steel frames. As steel is a ductile and resilient material, characteristics very different from concrete, acrylic was clearly not a suitable material choice. The research into available plastics revealed that acetal (Delrin), a common substitute for metal parts in small machinery, displayed the necessary characteristics. Acetal is an industrial polymer that possesses many desirable qualities, such as a low melting point, high degree of machineability and incredible durability. Our use of acetal in the production of the steel structural models opened a new set of possibilities and inspired additional investigations. Its material response is ideal for the fabrication process and has, through intense and repeated detailing shown great results in replicating steel members in compression. It has been an ideal material for the intended instructional set due to its elasticity and low material memory, which allows it, even in high or over-stressed situations, to return to its original shape. This allows the steel series of models to be used repeatedly without replacement or permanent deformation.

The next challenge in the series of steel models was to find an accurate method to model the behavior of tension-only X-bracing members without the use of mechanical fasteners or adhesives. While acetal was incredibly successful in the demonstration of the buckling of slender steel members under compressive loads, its inability to stretch prevented its further use for tension applications. Under the influence of a lateral load one member of the X-bracing goes into tension while the other goes into compression. Acetal performed well in compression but caused the other members in the frame to buckle because of its refusal to elongate, and thus returned an inaccurate illustration of the system. In addition, fabricating this form of bracing was not possible utilizing only one layer of material because no matter how thin the link between the braces bacame, they were still rigidly connected and again did not truly illustrate the system. What was needed were two braces that were free to rotate in response to loading independent of one another. We realized that we needed a modeling material that could portray the behavior of a pair of independent cables or tie-rods at the given scale; this material must be capable of buckling under compression and elongating under a load reversal from compression to tension. At this stage of the project we began experimenting with sheets of silicone, neoprene, and gum rubber in a variety of thicknesses.

Through extensive experimentation with silicone and attachment detailing the X-Brace configuration, composed of two separate 1/16” silicone members tightly-fit into a 1/8” acetal frame, became the optimum illustration for the structural forces at work. Further experimentation with pre-tensioning and detailing yielded a system that would remain taut and fixed within the frame.

In excess of three hundred TOIS later, we are currently designing a system that will demonstrate the response of flexible diaphragms (such as plywood) to lateral loads. This necessitates the introduction of spandex to our material palette to simulate the way in which the diaphragm absorbs the deformation itself. When we attempted to represent a rigid diaphragm it became apparent that the TOIS system would have to be reconfigured. To this point all of the TOIS we have produced are two-dimensional but to successfully illustrate a rigid diaphragm a three-dimensional model is essential.

In contemplating the next generation of TOIS we realized that we must now move from the exclusive use of an over-head projector, to include the use of a document camera. The former method of projection works fine for two-dimensional objects but los-

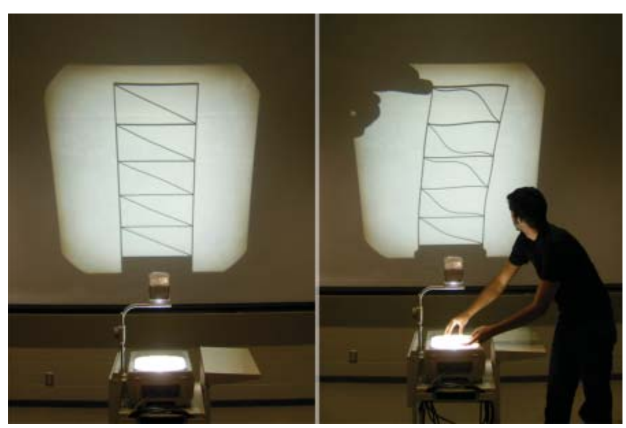

Figure 4. Presentation of T.O.I.S model on overhead projector

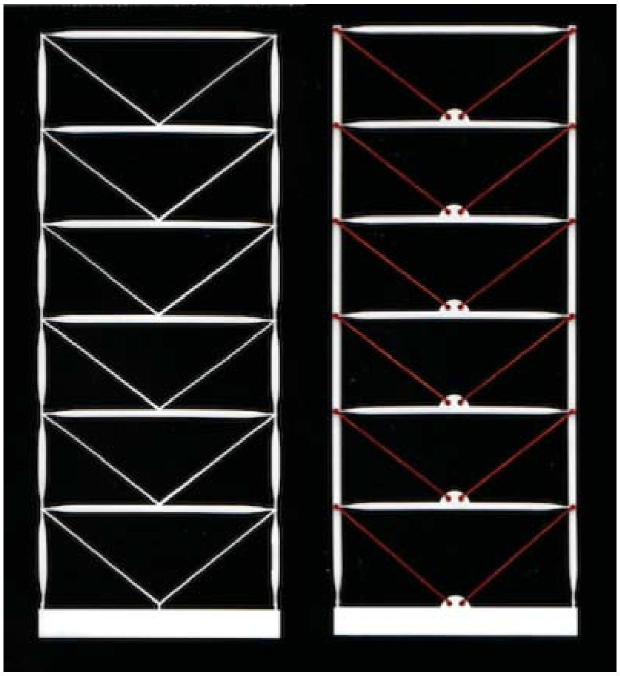

Figure 5. Chevron bracing schemes

es clarity in three-dimensions. The irony of these technologically fabricated models being viewed by means of the antiquated, but tried and true overhead projector, has not escaped us.

We have been busily playing with our TOIS for over a year now and have not yet reached the end of the system's potential. Throughout the project we have experienced the meaning of mass customization first hand. Mass production within this study has never been our objective, but through the use of our digital fabrication lab it is certainly provocative. This mass customization has become an area of interest in the machine's ability to create masses of customized, "one-off" products that are uniquely articulated and structurally responsive. Digital technology has allowed us infinite opportunities to experiment and to "tweak" our models without the prohibitive time commitment that would have been necessary, if these models had even been possible, through manual means.

So, as is so often the case, "one thing leads to another", and so continues the quest to find a better mousetrap, or in this case, a better way to explain structural principles to architecture students.

ENDNOTE

1. Torroja, Eduardo. Philosophy of Structures. Los Angeles. University of Califonia Press 1958