Haptic Structures: The Roll of Kinesthetic Experience in Structures Education

Deborah Oakley
University of Maryland

Introduction

As predominantly visual thinkers, many architectural students find courses in structural technology distant and abstract, especially when presented as mere "watered-down" versions of comparable courses taken by their peers in civil or mechanical engineering. While they may learn to do the mathematics with some proficiency, complaints can also be heard simultaneously that they have no idea what it all really means, or that they don't see the connection to actual built structures in the stick diagrams of beams and so on that they learn in class. This is both a shame and a missed opportunity, because of all of the allied engineering disciplines, structures is at once the most immediate (i.e., no structure means no architecture), as well as potentially the most form-shaping of all.

It is my contention that everyone to a greater or lesser degree possesses some amount of structural "instinct" or "gut sense," simply because our very own bodies are physical structures subject to the forces of gravity and wind, among others. The basic act of walking, for example, is an incredibly complex feat of balance and motion that young children of a certain age nonetheless perform subconsciously with ease. And yet for all our advanced technology, even today's most sophisticated robotic devices have yet to truly master this task. While conscious awareness of this structural gut instinct varies widely among individuals, it can nonetheless be stimulated and leveraged as an aid to conceptual structural understanding, as well as itself strengthened through reflection and practice. Furthermore, it is possible to draw upon this sense in connection to the mathematical calculations associated with the discipline to aid in making sense of what could otherwise be perceived as abstract notions.

What's Haptic-ning?

I've always liked the sound of the word "haptic." These days It's all the buzz in virtual reality circles, with devices that are enabling users to interact with computer systems by using resistive joysticks, sensing gloves, and a host other mechanisms in development. These devices can provide tactile feedback in a virtual computer simulation of the world much as one would experience resistance in actual direct contact in the physical world. The word itself derives from the Greek *haptesthai, which means* to touch. We gather information about the world though our senses, and the sense of touch is the most fundamental of all.

Accordingly, encountering resistance in a material is inherently different from merely reading about the same property in a textbook. It is this feedback loop of material contact that is capitalized upon when we incorporate hands-on experiences into coursework. More than 150 years ago American naturist/ philosopher Henry David Thoreau made similar observations of students in his own day when he wrote "*Which would have advanced the most at the end of a month,—the boy who had made his own jackknife from the ore which he had dug and smelted, reading as much as would be nec-*

essary for this,—or the boy who had attended the lectures on metallurgy at the Institute in the mean while, and had received a Rogers' penknife from his father? Which would be most likely to cut his fingers?" (Walden 65)

The use of physical models in education is, of course, nothing new and is a time-honored tradition to teaching in the sciences, such as in physics classes. In carrying on this tradition, then, there are a variety of simple lab exercises, classroom demonstrations and experiences I introduce to beginning structures students periodically throughout each of our two-semester sequence. Some of these are full-fledged lab experiments with a more formal rigor, while others are designed to illustrate concepts that are often difficult for new students to grasp, such as moment of inertia or restrained column buckling. Not only do they aid in conceptual understanding, but students who find technical courses challenging often excel at the hands-on experiences, and furthermore the perceived dryness and drudgery of structures as a discipline can be lessened. In addition, design can be allowed to enter in and an element of playfulness added.

Nowadays, "active learning" is the term used to describe an educational environment that encourages the participatory involvement of students in the their own learning experience. So now, a century and a half after Thoreau, academia has finally caught up with his forward thinking and active learning is itself a domain of pedagogic scholarship.

Hands-on lab classes thus form an important active-learning component to my structures classes. Typically, I try to create conditions of failure that can be analyzed and discussed to better understand how to create safe structures. This paper briefly describes several of the types of experiences that been used over the years in conjunction with the more traditional lecture period. Each type of project uses simple and readily available materials to keep costs down, while at the same time not cutting short the educational value. The lab assignments normally require a brief write-up to ensure both accountability and to facilitate retention, not to mention serving also as a checkpoint on student attendance.

Elasticity Lab: The Power of Plastic

The elasticity lab capitalizes on the properties of ordinary plastic bags to simulate a material tension test with results that very closely mimic those of structural steel.[1] You don't need a massive and expensive Tinius-Olson test machine to reinforce the basic concepts of elasticity when common trash bags will do the trick just as well.

This lab evolved out of an observation I made many years ago of certain types of plastic bags. I found that when cut into strips and stretched, they would exhibit a mild amount of elastic behavior and would return to their original shape when the force was released. With continued increase in force, however, I noticed a decided yield point where permanent deformation would set in beyond a certain level of stress. Furthermore, I noted that with continued force application the yielding would continue throughout the length of the strip until the entire length was yielded (with a surprising amount of elongation). After this point, the material entered a strain-hardened phase whereupon the "stretchiness" became con-

Figure 1. Elasticity lab using strips from plastic bags

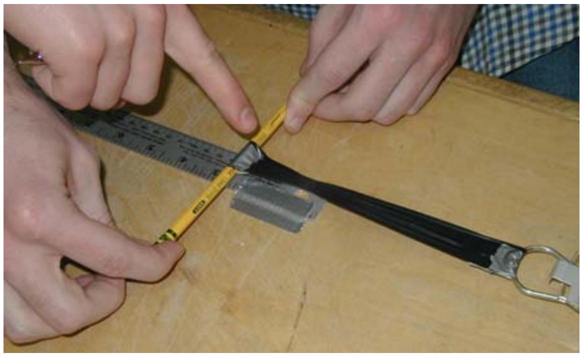


Figure 2. Moment of yielding in plastic strip

siderably less and the material noticeably tougher, with a significant increase in force capacity. Further increase of tension on the plastic, though, eventually resulted in a very sudden rupture of the strip with a strong "snap!"

This at first was a random observation that worked on various materials like bread bags, shopping bags and so on., but definitely not all. Finally after considerable experimentation the ideal material for my purposes was determined to be heavyweight industrial-strength black plastic trash can liners. It was obvious that its force/ deformation behavior mimicked structural steel to such an extent that it would be worthwhile formulating in a lab fashion. Furthermore, this material has the very nice characteristic of changing to a light shade of grey (almost translucent, in fact) that makes recognition of the yield point very obvious. It also turned out to be an extremely affordable learning experience as well. Besides using a material that from its very inception is destined for a landfill, the only additional supplies needed were a linear spring scale, a yard or meter stick, and duct tape. *(Figure 1)*

In conducting this as an in-class lab experiment (and even knowing that the characteristics of this material were so similar to structural steel) the outcome was surprising even to me. As can be seen in Figure 3, the resulting force/deformation graph for the plastic is strikingly similar to a typical stress/strain graph for mild structural steel found in any elementary text on structures.[2]

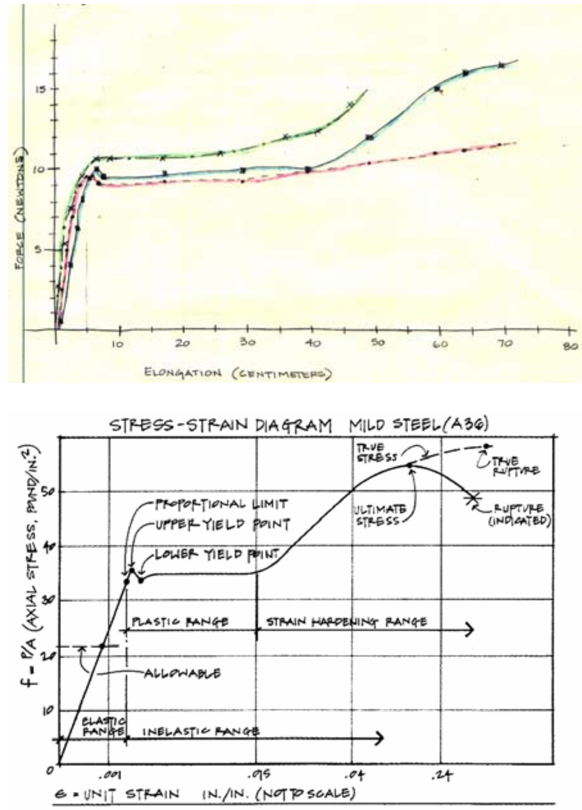


Figure 3. Comparison between lab class graph results (upper image) and stress-strain diagram for mild structural steel (lower image).

By having students take the force/deformation measurements and create this graph, related discussions of material elasticity and stress/strain diagrams take on an added dimension beyond a cursory reading; students begin to develop a *feel* for a common building material that would not otherwise be possible, simply because of the magnitude of force needed for similar experiments in steel. Nevertheless, as important as this outcome is, I don't stop with just creating the graph. Many additional valuable lessons can come from this simple experiment.

Having completed the experiment and logged all measurements, students are next required to compute the approximate structural properties of the plastic material. Knowing the amount of force at the yield point and the cross-sectional area of the plastic strip (they are simply given the bag thickness as being 4 mils), the stress level at yield may be calculated. Having measured the amount of deformation at yield relative to its original undeformed length, the strain be computed. Now, having calculated these two values, the approximate elastic modulus for the plastic can be determined as stress divided by strain. Normally, I will also give some of this information in mixed units (e.g. the plastic thickness and width in inches and the force and deformation in SI) to reinforce the process of dimensional analysis in calculations.

After computing the yield stress and elastic modulus for the plastic, the next step is to make comparative calculations with the material they've been replicating, structural steel. In calculating the ratio of stress and elastic modulus of structural steel to that of plastic, students learn that while steel is close to 100 times the *strength* of the plastic, it is on the order of tens of thousands of times *stiffer* than plastic. And so the significance of, and the distinction between, strength and stiffness is facilitated by this exercise—a common struggle for many new students to otherwise understand when presented in the abstract.

In addition to all of the above, there are yet more lessons to be wrung from this experiment. From here we may proceed to discuss other important related phenomenon in a conceptual manner. First, many of the strips will (despite taking care in cutting) end up with irregularities that result in premature failure before the entire length has yielded. The concept of stress concentration then becomes vividly significant.

Second, discussion of the concept of isotropic versus anisotropic materials is also possible. Although it seems natural to assume that, since the plastic is apparently uniform and homogeneous, it will respond to stress the same in all directions. In a related (and accidental) discovery about this material, though, I noted that the clear yielding behavior is true only in one direction (crosswise to the length of the bag)[3] There is effectively a "grain" to the plastic even though it appears uniform. Demonstrating this in front of class with strips that appear identical (I use a video display projector to show them more clearly to a larger class) makes it obvious that there can be surprising differences in a material's response to force application depending on how it is oriented.

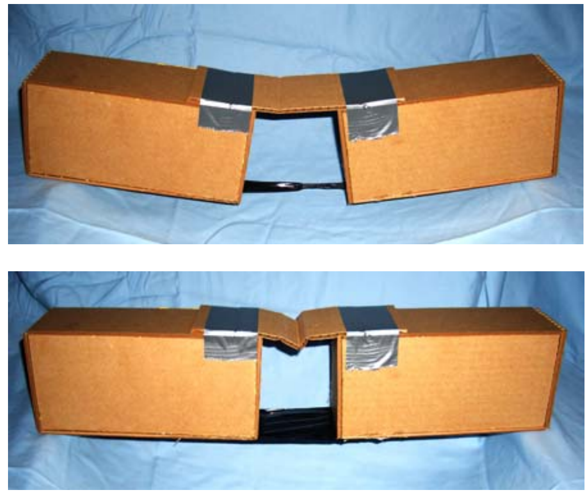


Figure 4. Pseudo "concrete" beam of cardboard using plastic bag strips as bottom tensile reinforcement. Ductile failure of under-reinforced beam (upper image) versus brittle crushing behavior of over-reinforced beam (lower image)

Lastly, during the initial lab experiment as the tensile forces become higher, often the tape holding the plastic will come loose. This can be discussed to illustrate the importance of secure connections, or in the case of steel reinforcement, the idea of bond and development length.

So, as can be seen, from this one simple and inexpensive experiment all of these vitally important concepts of structural materials can be not just talked about, but viscerally *experienced* by students. Through this activity, a lasting experience is possible that makes the abstract idea of elastic modulus and other material properties very real.

Before ending this discussion about the elasticity of plastic bags, it is very much worth noting another related demonstration. In this case the plastic strips can be used to describe the behavior of reinforced concrete. Here, the composite action of steel and concrete is replicated by using the plastic as "tension steel" in a cutaway beam section (I use a simple box beam of corrugated cardboard), with a strip of corrugated cardboard as the "concrete" in compression. By varying the amount of plastic used as reinforcement, the concept of under- reinforcing a beam versus over-reinforcement is made dramatically clear. Students learn vividly why the notion of "if a little steel is good, then more must be better," is a mistaken one.

With a small amount of the "plastic steel" in place at the bottom of the beam and pressing down with one's hands, a very ductile and flexible member is developed, one that exhibits a sizable amount of deflection under load. But in replacing the small amount of plastic with a much larger amount, the beam becomes stiff, rigid and unyielding. The failure is shifted from that of a gentle, ductile stretching of the plastic to a sudden almost violent crushing of the cardboard. Few students have trouble understanding why "under-reinforcing" a concrete beam is actually a desirable and good thing after that.

Although performed only as a demonstration and not yet developed into a lab experiment, this could easily be done. One of the lessons beyond the over- under-reinforcement concept could possibly include computation of the internal couple moment in resisting a measured applied load and corresponding external moment. And as described above with the elasticity lab itself, the importance of proper bond of the reinforcement c an be illustrated through varying the length of duct tape used to attach the plastic strips to the beam. If the tape comes loose before either the plastic yields or the cardboard crushes, then clearly a bond failure has occurred and a longer length of tape is needed!

K'NEX…or, "Did Somebody Say Triangulation?"

K'NEX are a children's toy based on a kit of parts that are most fundamentally a set of rods and connectors. An absolute trove of ancillary parts including decorations, small battery-operated motors, tiny doll-people, roller coaster carts and so on are also available. But for the structures class, however, the elements of greatest interest are the rods and connectors. The K'NEX corporation has been a wonderful supporter of education in the past, and has graciously provided donations of materials from production overruns, irregularities, demonstrations, and so on for use in my classes.

If you are not already familiar with this popular toy, the concept is quite simple. The rods

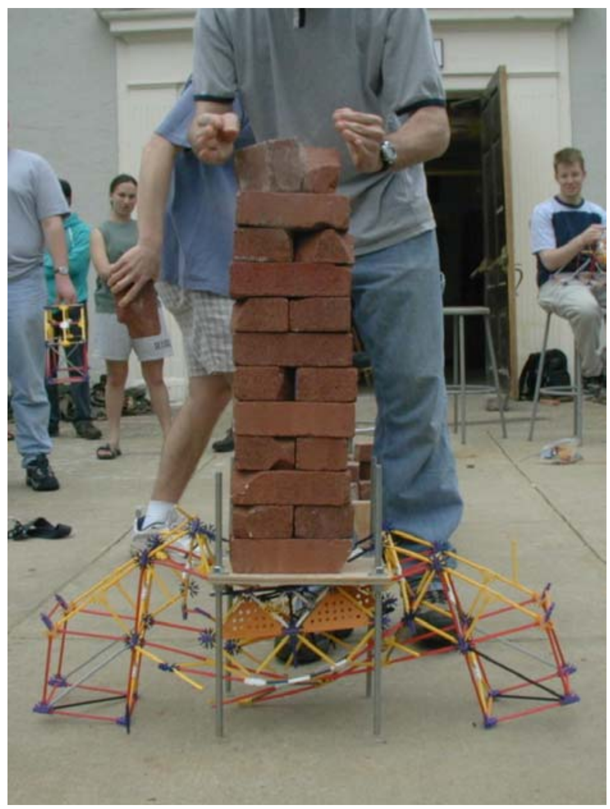


Figure 5 Bottom chord tension failure of K'NEX truss loaded with approximately 120 pounds of bricks.

(which snap into place with the plastic connectors in a tab-and-socket fashion) are of

Figure 6. K'NEX beam loaded by cantilever arm with sand bucket filled from upper bucket. Lateral-torsional buckling clearly evident as failure mode (lower image).

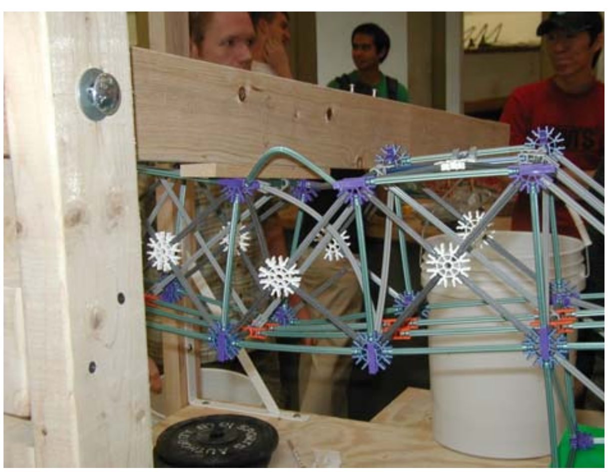


Figure 7. Top chord compression failure of K'NEX rod

advancing by the square root of two. Thus a right triangle is formed by two rods of the same size on two sides, plus one rod of the next size up on the third. Approximately a half dozen sizes of triangulation are possible through this scheme. The connectors range from straight in-line, to 45º to 360º around and all angles between at 45º increments. Furthermore, although the basic connectors are planar, there are certain types that connect to one another orthogonally thereby making spatial triangulation possible. It's simplicity and flexibility is truly genius.

Students enjoy working with these because they are quick and easy to manipulate and construction can be readily modified. I have used these as the "Magic Bullet" (to use Ed Allen's term) of my first structures class to have students build truss bridges with very little direction beyond giving them the pieces and having them span a given distance to carry the most load with the lightest structure possible. Loaded with steel weights, they learn not just the significance of triangulation in a spanning element, but many other important considerations.

Since the trusses are to be free-spanning between the ends (a 30 inch span is about right), a very common failure mode is lateral-torsional buckling. They see that proportionally lower and wider cross-sections are far less prone to this failure than taller-narrower approaches. Nevertheless, they also learn that there is a limit to how flat one can build as the depth of the truss is seen to correlate to the absolute load it can carry.

Joint separation is the most common failure mechanism and is really the greatest weakness of the system in a tensile load. I do, however, make them aware of this weakness beforehand and challenge them to find a workaround for it. *(Figure 5)* Students can be very ingenious with their solutions, which range from overlapping parts much as one would overlap wood in a laminate, to simply altering the direction of the connector.

A much more rare occurrence that really happens only in the members which successfully address the lateral-torsional buckling and connector issues, is when one of the compression rods will actually buckle under load. *(Figure 7)* Each of the aforementioned failure modes becomes an opportunity for discussion in relation to their significance in horizontally-spanning truss members.

I have gone through a number of variants on this particular exercise. As noted, one has been as the "magic bullet" first class exercise, and it has proven to be very successful in that manner, especially when I "close the loop" and provide feedback on the designs to the class as a whole. The "winner" of this project is the one that demonstrates the greatest load capacity to self-weight ratio, with runners-up being those of ingenious design or possessing other unique attributes.

I have also used this project is as an end of the semester competition where the truss is designed to be free-standing across the span, and once as part of a "Rube Goldberg device." In this elaborate scheme, not only did the students create the trusses, but the loading was done through a lever arm with a bucket of sand attached. The twist here was that the sand bucket was filled from above by another bucket that initially is plugged by a rod. *(See figure 6)* This rod was knocked out (starting the sand flow) as the end action of the "Rube Goldberg contraption." The device itself was left open to the imagination of the students and some were truly ingenious.

In place of horizontal trusses, I have had students perform compression tests of K'NEX columns as well. *(Figure 8)* The failures of these projects are typically less dramatic than the trusses; however, it is really quite surprising how much load they can be made to carry. Load capacity to self weight is here again the criterion, but the discussion of a variety of failure modes becomes possible, including overall buckling versus localized buckling, torsion, and accidental load eccentricity and the P-Delta effect.

Figure 8. K'NEX column load test. Note Buckling of various rod members.

In other applications of this very flexible educational device, they can be used in conjunction with discussions of lateral loading. Clearly, as triangulated members the application as vertical trussing in a building frame is a natural one. But a simple horizontal two-bay box structure can be used in conjunction with a linear spring scale pulled by hand at the upper center joint to demonstrate progressively: A flexible roof diaphragm with horizontal or lateral trussing (it is effectively a semi-moment resisting frame); a braced frame with flexible diaphragm by trussing each side but not the top; and a rigid diaphragm with braced frame by trussing both the sides and the top. *(Figure 9)* Progressing through this sequence and measuring the amount of force the frame will take, one moves from a rather flexible to an absolutely rigid structure, with

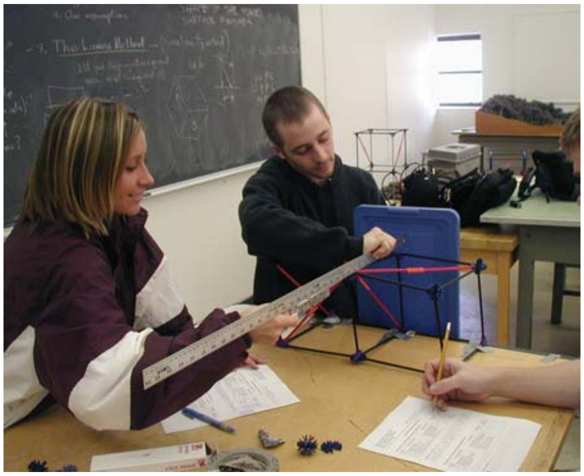


Figure 9. Lateral forces lab. Measuring horizontal deflection of two-bay braced truss frame

a corresponding increase in capacity for lateral resistance and decrease in the amount of horizontal deflection (drift).

Continuing the demonstration (or lab) above, if only one side is braced, the structure with a load at the center will experience a clear torsional rotation, thereby illustrating the importance of symmetric bracing. If the top diaphragm bracing is removed, the amount of torsion is reduced considerably, showing that flexible diaphragm systems can be safely designed by ignoring any effects of torsional loading.

Lastly, the horizontally braced top diaphragm with one vertical side brace can be again modified, this time with an orthogonal *pair* of truss members on the sides perpendicular to the loading. The amount of torsion is again reduced to nearly zero, thus illustrating the concept that a structure with bracing located eccentrically from the centerline of loading will not experience torsion if at least two orthogonal walls are present. Remove one of these trusses and most of the torsion will return, thus reinforcing this understanding. If calculations are introduced, one can compute the magnitude of the resisting couple forces by simply measuring the moment due to the measured applied force and the distance away from the parallel braced wall, and dividing by the space between the couple walls.

These are just a few of the many ways this versatile child's toy can be employed as a kinesthetic sensory experience of structural behavior. Taken as a whole with all the variants possible, K'NEX is one of the mainstay devices I use for physically modeling structural behavior in my classes at all levels.

The Impossible Cube

As with many who teach building technology or structures, I find that the work of Santiago Calatrava provides for a fount of exemplary material in contemporary design. We drawn upon this for illustrative examples in projects that unite and express engineering principles clearly as an intrinsic part of architecture. Lesser known, however are Calatrava's sculptural works, many of which push the boundaries of structural potentialities and seem to defy gravity. I use these both as examples and, in once case, as an inspiration for a particular student project based on his many "cube" sculptural studies. *(Figure 10)*

I began having students make these "impossible" cubes a number of years ago in small-scale models as a way to bring a sense of art and design into structures

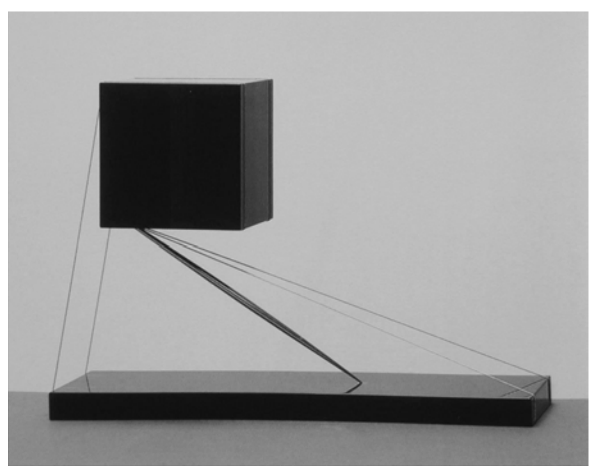


Figure 10. "Head XIB" Cable and single strut-supported ebony cube by Santiago Calatrava[1]

class. Although the project does not involve calculations (the three-dimensional statics are a little too involved for an introductory class), it nevertheless draws once again on the haptic principle of getting a real "feel" for balance and stability, plus it's just a fun project in and of itself.

The assignment is basically simple. Students are asked to provide a support for a cube of solid wood 4 inches on a side in a non-redundant manner, such that the removal of any one element will lead to a failure of the entire object. *(Figure 11a)* The primary restriction is that the supporting members cannot have end fixity…stability is to be achieved by the use of tension cables only.

It is important that the cube of wood be solid so that its mass will be distinctly activated by gravity. In the past some students have made them hollow and, while they may look nice and appear to address the project statement, at a small scale it is easy to "fake" the support and have it stand up merely by friction or stiffness. It is definitely acceptable (and I tell them desirable) if the cube sculpture is stable only in one configuration such that if, for example, the sculpture is turned upside-down it will fall apart. The goal is to find the absolute minimum members that will achieve both vertical and lateral stability, and to search for the underlying structural elegance in that minimalism.

Some students really fly with this problem and come up with some truly inventive designs, but any serious attempt provides for a meaningful learning experience. Most fundamentally they are learning the necessity of spatial triangulation involving one strut and two cables in a pyramid formation. Such a configuration can provide for both vertical as well as horizontal load resistance, and even in its simplicity a huge number of variations are possible. Another understanding is of learning just how difficult it is to construct something that appears so simple…it becomes evident to all that having several extra hands would be very helpful in the construction of these models!

Figures 11a & b. Cube project at desktop model scale and full-scale erection.

While this project has been done most often at a desktop scale, one year I ramped this up to the large size with cubes three feet on a side. *(Figure 11b)* For this class it was done in a two-stage group process. Teams of seven or eight students broke down into several smaller groups, each of which created their own design. These models were reviewed and discussed in the same manner as I had done in previous years. From here, though, each of the overall teams then chose amongst themselves which of the several models they most wanted to build at a large scale.

On their own and outside of class period, each team then worked as a whole to produce the components of the large-scale model. To reduce the weight and alleviate excessive lateral force due to wind loading, the solid "cubes" at the large scale became hollow frames with mesh or screening to give the appearance of being solid. One class period was set aside for the erection of the cubes with each team working together, and the new challenges posed in constructing at the large scale became evident to many of the teams. Some who thought they had figured out the stability of their small-scale model, for example, learned that when gravity *really* came into play, they had in fact overlooked something and some quick field adjustments were necessary. Other groups encountered situations they had never thought of, such as the unpredictable response of soft soil to a large lateral thrust from a strut. In the end, though, all of the teams had a successful installation of their projects. These large-scale "impossible" cube sculptures were then on display for the entire school and University to enjoy for about two weeks afterward.

Seismic Shaker Table

One of the more important considerations that I spend a sizable portion of the second semester on is stressing the importance of designing structures for lateral forces. Although our school location on the east coast means that for most of our graduates the significant lateral force they will be confronted with is hurricane wind load, I spend a reasonable amount of time introducing the principles of seismic loading and proper design to mitigate undesirable effects such as torsion or poor design choices such as soft stories. With increasingly stringent seismic design requirements of the IBC, more and more projects on the east coast must also be checked for earthquake loads in areas that in years past had no such requirement.

As a supplemental learning exercise to this, study, I have introduced a small seismic shaker table consisting of a platform attached to a bearing supported frame that has eight centering springs (two on each side) connected to an outer frame. By applying force to the platform in any direction, the centering springs will always move it back to the initial position. The platform can be moved simply by hand, or I have also an eccentric arm that connects to an ordinary cordless drill to act as a constant shaking force. By varying the speed of the drill, it is possible to get harmonic motions in tower models (for example, those made of K'NEX or basswood).

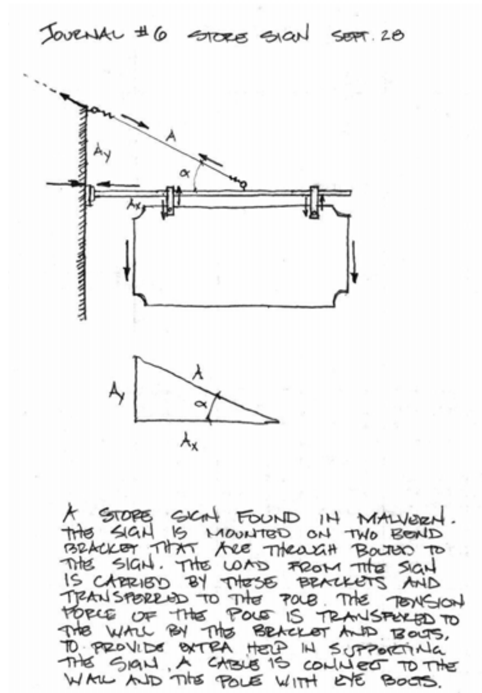
As an end-of-semester project one year, I had students create what I called (with tongue firmly in cheek), the "Im-Pastable" tower, which was made of ordinary spaghetti and hot melt glue. *(Figure 12)* The 18" high towers were locked to the table with hold down plates and a brick affixed to the top. Varying speeds of drill-induced oscillations were then used until the towers were shaken to destruction. The criteria this time was not really how much load the

Figure 12. Soft story failure of pasta tower in shaker table test

tower could carry, but rather for how long it would carry the load under shaking. Each pair of students in a team was given an ordinary one pound box of spaghetti to work with, and as usual the design criteria was to make the least weight structure possible. Surprisingly, though, the hot melt glue imparts a considerable ductility to the otherwise fragile spaghetti and some of the students made towers from that were strong enough to actually stand on! Needless to say, it was not possible to break these on the shaker table, and thus not really possible to ascertain the true strengths and weaknesses of a the design. In future offerings of this exercise, I have learned that a much smaller amount of material will perform well for this task to ensure that the tower can in fact be broken by the shaking alone.

The Structures Journal

Although there are other projects and demonstrations I do with my classes (for example, see Figures14-16) I will close this discussion with another valuable experience, although it is not a lab-type experiment such as previously described. This exercise I call the “Structures Journal,” and serves as a vehicle for helping students become more aware of structures they have seen all around for their whole life but have never taken notice of. As an engineering student, one remarkable professor I had for fluid mechanics introduced me to this exercise and it has left a memorable impression on me ever since. The guidelines of the experience were remarkably simple: “Keep a log/journal of fluidic phenomena in the world around you.” In performing this weekly exercise I suddenly found myself looking at all kinds of things like the way water drained in a tub, the wafting of smoke in the air, or the ever changing patterns of rolling and billowing clouds–all familiar phenomena now seen in a new light. Inasmuch as the calculations we learned required quite a bit of high level integral calculus, I found the journal to be a welcome reprieve from this density and struggle, and helped bring to life the more abstract mathematical formulae.



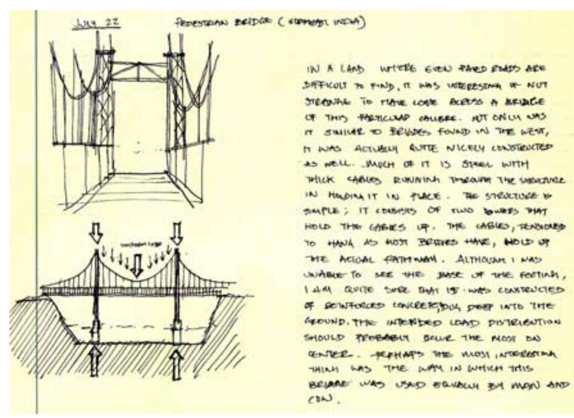


Figure 13. Example structures journal entries

And so in this spirit I have introduced this project to my own students, though this time oriented to structures. *(Figure 13)* Since one of the important notions I try to impart is the ubiquity of structures in the world, in their once weekly journal entry, I ask that they make five entries from structures they observe in the natural world (plants, animals, etc.), five from the object scale (tools,

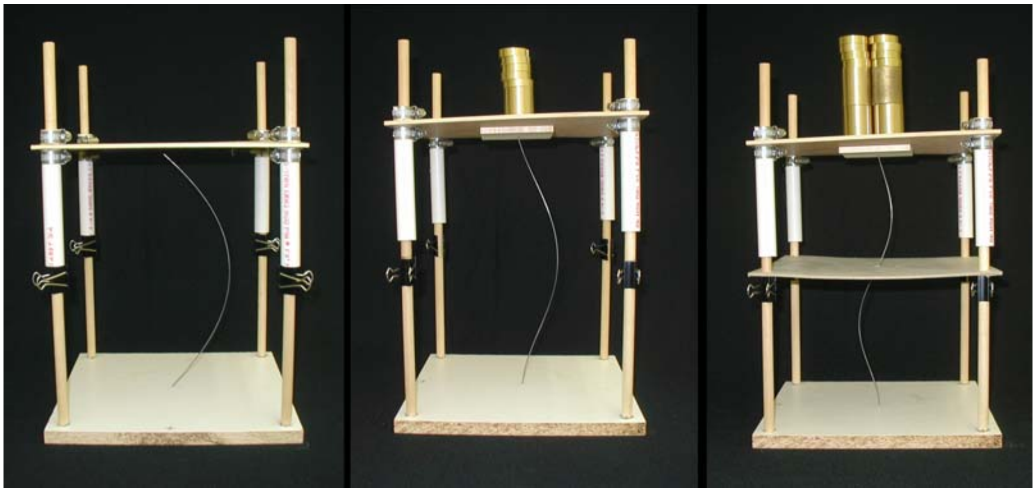


Figure 14. Substantial increase of column buckling load capacity illustrated by progressive alteration to end fixity and intermediate bracing conditions on 1/8" diameter piano wire.

household articles and so on), and five from the architectural scale (buildings and bridges). As we go through the semester, I ask that students try to relate their observations to material we are currently studying. For instance, if we are covering moments and rotational equilibrium, to look at this phenomena in specific. *(See figure 13)*

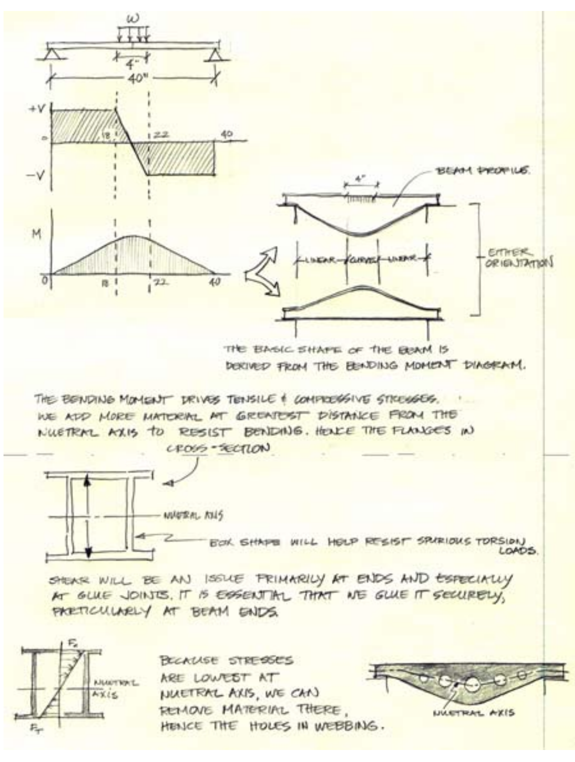


Figure 15. Student design of cardboard beam tested in lab class

Conclusion

Structures classes for architectural students have a fundamentally different role than comparable courses for students of engineering. For the most part architects will not be designing actual structures aside from perhaps smaller-scale projects, and even there the role is normally quite limited. Yet the realm of architecture encompasses the holistic perspective of buildings in their entirety, including learning to properly plan and proportion their structural systems. If a building structure is properly conceived at the schematic level, then when actual engineering design *is* undertaken, it will be much more likely that wise choices have been made such that the engineer is not fighting against the forces of nature for sake of a structurally ill-informed architect's dream. While I personally have a penchant for structures that unite architecture and engineering as an inseparable whole (my heroes being the likes of Kahn, Nervi, Foster, Candela, Calatrava and so on), I also accept that my students may not share this value. Nevertheless we live in an era of rapidly growing awareness of the limitations and scarcity of our natural resources, and it is increasingly unconscionable that architects end up causing engineers to "force" a structural system to work by virtue of inap-

Figure 16. Test loading of cantilevered corrugated cardboard beam

propriate or inefficient designs at the most basic conceptual level. "Making" a structural system work, while almost always in some way possible, is rarely if ever economical of means, or conservative of resources.

The above hands-on exercises may in some cases be short on numeric calculation, but are nonetheless long on conceptual import and are designed to facilitate the development of what has sometimes referred to as "structural intuition." Interspersed with the traditional calculations in this type of class, they can become an important aspect in the way structures classes are taught, and serve to reinforce and clarify the analytical components.

So, in the end, what do students think they get out of the exercises? Sometimes the results are clear in the enthusiasm and energy they display. At other times the reactions are harder to judge with results that are frustratingly mixed. Quite frequently I receive many positive comments about these experiences as being excellent reinforcements to other aspects of the class that also address variations in learning styles. Yet some other students have remarked that they are nothing more than superfluous busywork. One student for instance commented that the full-sized cube structures seemed to be nothing more than "for show." Or take for example the case of the structures journal described above. The results of this exercise have produced some truly outstanding observation records by a number of students that clearly reveal a deep level of engagement with the material. Surprisingly, though, when polling the class anonymously, the exercise received a resounding thumbs down.[4] In looking at the journal entries, though, it seems that although ostensibly unpopular, many students do not really realize just how much they are learning through the process.

Nevertheless, despite the lack of universal student acclaim, I am a firm believer in the importance of these exercises and will continue to employ them. I will, however, continue the search for an optimal balance between the kinesthetic experiences and computational aspects of the classes. In this quest, I welcome feedback from others on this approach taken to making structures both more engaging as well as a more rich learning experience, one that leaves a lasting memory and positively influences the understanding of fundamental structural behavior.

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Notes

[1] For a complete description of the lab including directions on how to set it up and record measurements, see "Technology in a Trash Bag" in the Summer 2006 *Connector* newsletter.

[2] The purist will argue that there are certain inaccuracies in the process, the most significant being that the measured deformation is not simply that of the plastic, but also that of the spring in the scale. But in the overall scope of things, I believe this to be of minor consequence, and that getting overly technical and detailed in the process would only obfuscate the underlying concept. Such refinements could perhaps be the topic of more advanced lessons.

[3] Not being a materials scientist I can only speculate that this is due to a linear alignment of polymer chains in the "up and down" direction of the bag as it would normally be placed in the trash can. Close inspection of the material in bright light revels subtle but definite and perfectly straight parallel striations along the length of the bag. I theorize that by tensioning *across* these polymer chains, one is effectively "opening them up" and the clear yielding behavior is happening by separation of the molecules. When stressed *along* the length of the polymer chains, one is merely elongating or uncoiling them without separation. I welcome clarification or correction of this speculation by any knowledgeable chemist!

[4] By way of personal response devices ("clickers"), an anonymous poll was conducted at the end of the spring 2006 semester. The question was posed as follows: "The structures journal has been a useful tool for reflection on material being studied in class." 37% of students disagreed and 45% of students strongly disagreed with this statement, indicating that some 92% of the class considered this exercise to be essentially without value. For a full description of personal response systems in lecture classes, please see my paper "Two Way Structures" elsewhere in these proceedings.