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Supporting Students Structurally: Engaging Architectural Students in Structurally Oriented Haptic Learning Exercises

Abstract

Beginning architecture students have traditionally been taught structural design using an engineering-based educational model. Often, information is presented in formula-rich lectures filled with abstract representations of architectural space. In other words, when structural design is presented as a series of calculations instead of a series of design explorations, educators miss a great opportunity to develop a better integration between structural information and other architectural coursework—and integration that would enhance design development by balancing technical resolution and exploration. A new educational model for teaching structural design to architects is needed. Architecture students should be given a series of exercises that help to develop their understanding about the relationship between structural form and forces, structural behavior, and the array of potentially responsive architectural forms. This paper will demonstrate how a curriculum based on experiential exercises, haptic learning methodologies and project-based design exercises in a laboratory setting can provide a more effective way forward in educating architects about building structures. Because initial exposure to complex topics can often make a significant difference in long-term learning efficacy, this paper will primarily discuss the very first lab project in the sequence, an ergonomic lab in which the students use their bodies to explore basic structural principles related to the relationship between form and forces.

Keywords

Body Structures, Haptic Learning, Structural Pedagogy

Disciplines

Architectural Engineering | Architecture | Engineering Education

Comments

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SUPPORTING STUDENTS STRUCTURALLY:

Engaging Architectural Students in Structurally Oriented Haptic Learning Exercises

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ABSTRACT:

Beginning architecture students have traditionally been taught structural design using an engineering-based educational model. Often, information is presented in formula-rich lectures filled with abstract representations of architectural space. In other words, when structural design is presented as a series of calculations instead of a series of design explorations, educators miss a great opportunity to develop a better integration between structural information and other architectural coursework—and integration that would enhance design development by balancing technical resolution and exploration.

A new educational model for teaching structural design to architects is needed. Architecture students should be given a series of exercises that help to develop their understanding about the relationship between structural form and forces, structural behavior, and the array of potentially responsive architectural forms. This paper will demonstrate how a curriculum based on experiential exercises, haptic learning methodologies and project-based design exercises in a laboratory setting can provide a more effective way forward in educating architects about building structures.

Because initial exposure to complex topics can often make a significant difference in long-term learning efficacy, this paper will primarily discuss the very first lab project in the sequence, an ergonomic lab in which the students use their bodies to explore basic structural principles related to the relationship between form and forces.

KEYWORDS: Body Structures, Haptic Learning, Structural Pedagogy

RESTRUCTURING A STRUCTURAL EDUCATION:

“The process of visualizing or conceiving a structure is an art. Basically it is motivated by an inner experience, by an intuition.”—Eduardo Torroja, 1958

At its most basic level, structural design is about creating strategies for “spanning and stacking” elements in interesting and effective ways. Although these challenges are elemental, the diversity of acceptably responsive solutions can become a staggeringly complex array of choices—choices that rely upon a broad and balanced set of design skills. Helping architecture students develop the skills to evaluate the pros and cons associated with selecting and arranging different structural choices is, at its core, a process of reiterative design.

Unlike other design courses, however, structural design also needs to impart a more specific technical acumen, often times involving a heavy combination of math and physics, that students need to critically assess and develop their work. However, this

often results in a teaching method that primarily emphasizes the importance of quantitative understanding and assessment—it does little to develop the qualitative aspects of structural design related to the interdependence of materiality, form, and structural behavior. Unfortunately, if the teaching methodologies and learning environments in the initial classes aren't effective, this can adversely impact efficacy of retention and enthusiasm for the topic. This problem is more profound in a multi-semester sequence of courses with graduating levels of difficulty, in which there is a necessary expectation of accumulated knowledge and skills from previous courses.

This paper will present the first lab in newly revised undergraduate structural design sequence at Iowa State University, called Structural Technology in Practice (STP). Courses are taught in five-week modules in a combined lecture / laboratory classroom setting for five sequential semesters. In hopes of providing a more effective means for educating architectural students about qualitative and quantitative aspects of building structures, this sequence has integrated a new pedagogical model for teaching structural design by integrating haptic learning methodologies into the coursework. Students are regularly asked to design, build, and sometimes break their structures in an attempt to better demonstrate how structures work and to see structural design as interactive.

During the first class of the new sequence, the *anthropomorphic structures* lab, students use their bodies to explore basic structural principles related to the relationship between form and forces. By constructing lightweight structural conditions, students developed an ability to analyze and describe the structural behaviors their bodies were enduring, including their first conscious exposure to variously intuitively understood structural limitations their bodies navigate daily. In many ways this lab is representative of many of the larger pedagogical goals for the entire sequence—it demonstrates the types of activities that regularly take place within the revised classroom setting, it reveals how these alternative methodologies are used to learn about essential, even traditional, aspects of structural behavior, and it shows how these methods of learning are reinforced in the manner by which students are allowed to represent and discussed their experiences.

THE FIRST LESSONS & STRATEGIES FOR LEARNING:

There are essentially three main priorities for initial courses in a sequence: teach foundational topics effectively by emphasizing conceptual understanding of behavior, introduce a range of various problem-solving techniques for students to try, and instill a sustained enthusiasm for the topic by presenting the relevance of the information taught in an engaging classroom setting. These challenges are made more profound in math and engineering based courses because the foundational topics are often based on abstract concepts of physical behavior that are primarily demonstrated using a single problem-solving technique (calculation-based proofs), typically in a passive classroom environment where the communication is one-way (non-interactive). When the means of presenting and processing information is too abstract, as it often is in traditional structural design courses, students are unable to visualize the concepts being presented and the relevance of what is being taught is unintentionally obscured. This leads to a fundamental problem. Teaching the behavior of physical phenomena, like structures, without offering

students a chance to physically experience it, results in a deficit of understanding about the principles of the subject (diSessa 1993).

Visualization skills are of central importance in structural design, and yet the capacity to imagine the consequences of structural behavior in complex systems without any conscious perceptible experience is extremely difficult—simply put, if one can't see what's going to happen in a structural system, then it's more difficult to design apt response. The initial challenge, then, is how to impart knowledge about these structural behaviors in a manner that enhances the capacity to visualize the potential behavior. One solution is to engage students in simulations of these situations in an effort to enhance their reasoning about the potential physical behaviors in certain situations—these simulation have been shown to be more effective than the use of visual imagery alone (Barsalou 2008). Integrating physical exercises with the course content strives to enhance the relationship between the body and the physical world, in an attempt to develop embodied cognition, which studies have shown help students to better visualize abstract behaviors based on their perceptual experiences (Black 2011).

Processing abstract information while physically manipulating objects is a proven method for enhancing comprehension, so throughout the entire STP sequence, the use of haptic learning techniques has been a matter of central pedagogical importance in both theory and practice (Williams & Franklin & Wang 2003). In nearly every lab, students have built, tested, bent, and often broken their structures in an attempt to better understand the inherent physical behaviors of how the structures work. And yet, at the beginning of the entire sequence there were very few types of structures that we could reasonably have expected students to construct and test in a critical manner. There was one critical exception—the students already intuitively understood the structure of their own bodies quite well, albeit mostly on an intuitive level. The hypothesis was that the most direct way of establishing embodied cognition was to simply ask students to create structures with their bodies.

STRUCTURALLY SUPPORTING STUDENTS:

The Anthropomorphic “Body Structure” lab was designed to effectively address the three principle challenges of early course work: how to establish comprehension of fundamental structural topics, how to present alternative problem-solving methods that promote better visualization, and how to teach representations of abstract content in an interactive environment. Students were encouraged to see how the choices they made intuitively about the arrangement of their bodies can reveal critical lessons about complex structural performance and design strategies.

The learning objective was to conceptually connect abstract terminology of structural behavior (e.g., forces, loads, stresses, and states of equilibrium) with the various physical actions undertaken in each scenario. After allowing students to experience certain elemental structural behaviors, and discussing these conditions with them during lab, they were asked to develop multimodal representations of what they experienced (pictures, diagrams, and descriptions) in a lab report. In the lab, they were asked to include information about a broad, somewhat complex interrelated set of elemental structural

terms and conditions: loads (dead & live, point & distributed), force vectors (sense, direction, and magnitude of components and their resultant), stress (compressive, tensile, bending, shear, and torsion), states of equilibrium (translational and rotational), and finally how and where each of these conditions was manifest in their body structures.

As a means of simplifying the relatively complicated and infinite series of potentially possible structural conditions, the lab intentionally presented only two simple and easily understandable structural problems to solve: Using only their bodies, students were asked to see *how far they could span* and *how high they could reach*. By being able to successfully complete these modest challenges, students realized that they *already* understood some aspects of structural behavior and that they regularly create effective, responsive, structural forms, even subconsciously in their daily routines. The process of standing, reaching, and holding objects is so common place that students often fail to recognize these seemingly innocuous activities solve the same structural challenges of “stacking and spanning” that all structural designers face.

This seemingly simple scope belies a much more complex set of learning objectives that could only be met by gradually revealing and suggesting several sub-set scenarios within each exercise for students to enact, such as adding more people to each situation, incorporating weights, and/or allowing walls to be used as part of the system. By slightly changing the factors involved, students reconfigured their structural forms that



Figure 1: Adjusting Body Form for Balance

transferred stresses to different components/body parts and often necessitated a different type of connection/grip to make the system stable. In other words, in order to maintain static equilibrium in a system, an integrated range of variables all need to be considered. This is a profound fundamental lesson that is necessary for more advanced structural design work, and it becomes one of the first lessons taught in their entire sequence.

TEACHING STABILITY & EQUILIBRIUM:

The concept of static equilibrium is usually taught by showing equal and opposite force vector arrows that represent the loads and resistance in a structural system. These arrows are represented only two-dimensionally so they do little to help students visualize the challenges of maintaining both translational and rotational equilibrium in a three dimensional system. Students quickly realize that actual structural systems rarely have forces that behave in a straightforward manner suggested by the arrows in the diagrams and they look to alternative methods to visualize structural behavior. One of the greatest initial benefits of the Anthropomorphic Lab is that students can instantaneously understand the complicated nature of equilibrium in structural systems by modifying their stances when they attempt to reach high or seek to find a balance in their body weights when they lean forward to reach farther (Figure 1).

In the spanning exercise, students often form chains with their bodies in which one or two other team members will lean out from an anchor point to reach as far as possible. Most of these exercises immediately reveal the importance of balancing the internal forces within a system as the shape of the structure they create often shifts and evolves the further out the team members reach. For example, sometimes when team members are the same weight, the students supporting the other leaning and reaching student will have a very hard time not falling over—in other words, they realized that the center of their combined gravity has passed beyond the line of support. They intuitively modify their structures by leaning back further and/or reducing the length of arm extension.

In one particularly helpful exercise, one student stands in the middle and allows two other students to hang off of each side. The hanging students consolidate their feet with the middle student and slowly reach outward for a dramatically long span (Figure 2). This pose teaches several key lessons about stability: the weight of the hanging students should be relatively balanced or it doesn't work (rotational equilibrium side to side), all the feet need to be grouped tightly together at one point



Figure 2: Rotational Equilibrium and Internal Stresses

(concurrent forces and rotational equilibrium front and back), and it demonstrates the natural formal rigidity of a triangle in a system (between their arms, torso, and feet). Few students can achieve this pose because of the heightened level of internal stress felt by the center student in their arms. Of course, this becomes a its own lesson as well.

STRESSES AND STRAIN:

The next observation that students usually make is that they “feel” certain forces differently within their body depending upon their configurations. Intuitively they come to realize that in order to maintain “external” equilibrium within a system that certain forces and loads must first be resisted “internally” by using the strength of their legs, arms, and torsos. Again, depending on the scenario, they realize that the weight of their bodies (or props) are the loads in the system and these loads created different types of stresses (compression, tension, bending or shear) depending on the configuration. Some body parts are better equipped to handle different stresses than others, so students intuitively resist bending with their elbows and torsos, compression with their legs, and tension with their hands and arms. As an example, in an attempt to reach high in a column structure, two students often hold a third student in the middle, either on their knees, waist or shoulders—this structure typically fails



Figure 3: Form adjusted to resist buckling

eventually not because the stance of the supporting students is out of equilibrium, but because the compressive stresses accumulate and fatigues the legs of the students nearly to the point of buckling (Figure 3). In later semesters when discussing the need to provide buckling resistance for compressive elements, such as columns, this lesson is brought up as an example.

Other types of stresses, which are relatively abstract in concept but essential in understanding structural behavior, such as moment forces, bending, and torsion are easily demonstrated in the spanning/reaching exercise. The concept of moment force is perhaps most easily taught by simply asking students to hold a weight away from their body at various lengths—obviously the further away the weight is held, the more their shoulder has to generate an internal resisting “moment” to keep their arm from falling down—simple mathematics are introduced here alongside other physical examples of shelf brackets and tree branches to show how certain shapes are designed to be form resistant against these particular types of stresses. When they are asked to reduce the length of their reach in half and comment upon the new type of force, they always respond not only that it is significantly easier, but some students note that the orientation of their arm greatly contributes to the capacity to resist this new bending moment because a bent elbow also allows the bicep to resist the moment force as well (Figure 4). When they are asked to twist the weight using their arm they can feel the affects of torsion. The students intuitively manipulate the overall form of their structures to reduce the amount of moments, and torsion in lieu of relatively pure compressive and tensile forces. This relationship between the types of stresses created and the overall structural system’s form become a primary learning objective of the lab and the entire sequence.

FORM RESISTANT STRUCTURES:

No matter the exercise, students rarely create any body structures with flat surfaces, right angles, or purely orthogonal arrangements—in fact, in their attempts to create equilibrium in their body structures and minimize the amount of resulting stress on their joints and muscles, the students intuitively create “form-resistant” structural shapes. The shapes, which mimic cable and

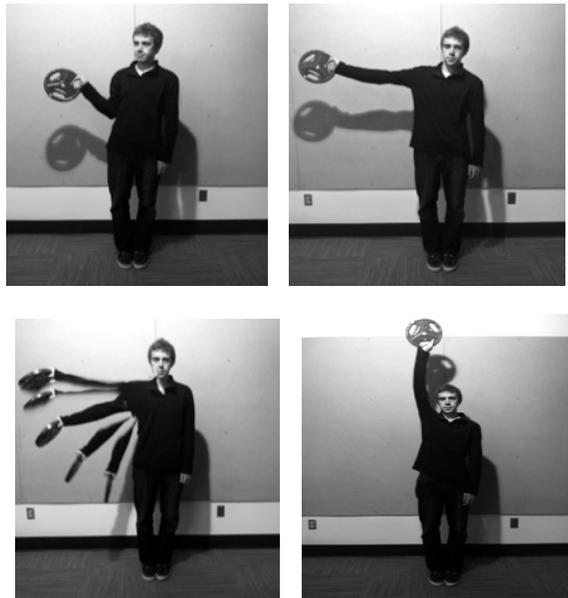


Figure 4: Moment Force and Lever Arm



Figure 5: Form-resistant geometries of the hanging cable and thrust-resisting angle of supports.

arch structures, are efficient structural design strategies that simplify the stresses within the system to tension and compression by manipulating the overall shape of the structure. This lesson is especially acute with one particular spanning exercise that some students attempt where two students hold up another student off the ground by the hands and feet to create a span as long as the student's body. In doing this, the spanning student's body naturally hangs down in a funicular shape to create complete tension throughout the body. This basic configuration provides an opportunity to talk about axial stresses in a system and the requirement that these types of systems must deal with the resulting thrust in the supports—the two students holding up the middle student often lean back with their entire body, pulling as a means of creating thrust (Figure 5).

Several times students have tried to make a longer “chain,” but no student group has been able to lift more than two students at once—the amount of outward thrust needed to lift the structure usually exceeds the students' capacity to maintain their grips in light of the heightened tension throughout the system. With poses like this, it is a great opportunity to talk about structural form and the resulting types and magnitudes of stresses and how they can create specific types of failures associated with these other choices, either a shear failure at connections or a stability failure at the supports.

SECTION ACTIVE SYSTEMS:

Finding the particular poses that are well suited to help extract lessons about structural behavior requires that particular poses or variables sometimes have to be enforced. In order to get students to understand the structural difference between form-active and section-active components (such as beams), students often have to be asked to manipulate their bodies to become more “flat” like a beam. Immediately these stresses manifest in their torsos and they find that the human body (particularly its skeletal frame) isn't particularly efficient in resisting bending at our mid-span! There are some students that try to span between two walls and create a beam between. These students will either: arch their back, cantilever both ends of their body off the wall (to reduce span), try to resist the forces with the strength of their abdomen muscles, or, most interestingly, rotate their torso to the side so it creates a taller cross section (Figure 6). By reducing the span or rotating to the side, they demonstrate the intuitive knowledge that changing the spanning condition and configuring the cross sectional are efficient lessons to resist bending (Underwood 1998).



Figure 6: In attempting to resist the natural curve suggested by the loading condition, the student feels bending stress.

STACKING STUDENTS:

For the “high reach” exercise, students often build a type of column/pyramid structure with their bodies. This is helpful in several regards. First, these body structures look relatively easy once the students are in their final pose, but the staging of their

“construction” is often quite complicated—there is always a lengthy staging and balancing of students as they construct themselves into their final form. Obviously getting students to think of structures not only as a final static form but instead an articulation of a complicated process of construction. Second, this exercise allows them to visualize and represent the impact that additive loads have on the base of a structure (Figure 7). When students are able to feel how much harder this is with one person on top of another, it is much easier to imagine the increased magnitude of forces and weight that act upon multi-story buildings. And third, the students at the base of the tower or pyramid nearly always triangulate their feet by shifting them forward and backward and side-to-side. Typically this weight shifting is an uncoordinated effort that is often unspoken and intuitive.

For this lab, there are very good opportunities to demonstrate a pinned connection by looking at ankles. Like pinned connections, ankles are designed to pivot with a certain amount of freedom of rotation—humans use this for balance and movement, in structures a similar type of connection is used to let columns move freely without incurring any bending moments. However, if you asked students if they would prefer to have ski boots on during this exercise to stabilize their ankles, many would gladly accept as they realize that this point of connection is a potential weakness of stability.

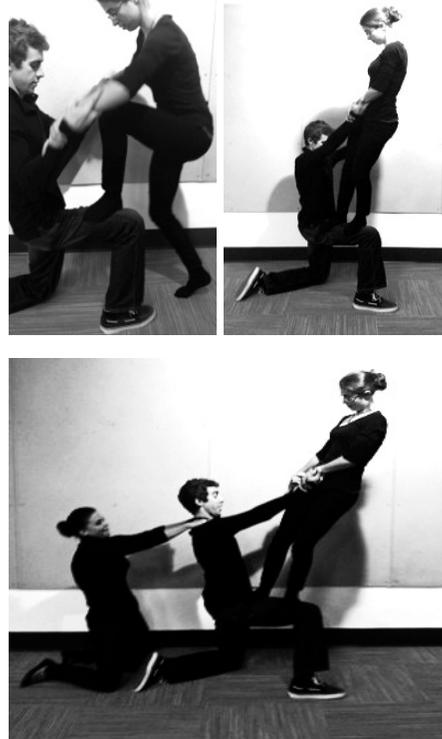


Figure 7: Tower structure involves a coordinated sequencing of erection and eventual reconfiguration of base supports to facilitate the most direct load transfer to the ground.

MULTI-MODAL REPRESENTATIONS OF ACTIVITIES:

In the more advanced structural design lessons in the sequence, there comes a time when the calculations and diagrams that describe structural behavior *must* be understood qualitatively and quantitatively quickly. The conventional representations and terminologies are actually quite useful as they describe a series of inter-related, tested, and measured variables that allow for experienced and knowledgeable designers to quickly assess the pros and cons of their design choices. Developing the capacity to have students engage in this level of co-variant reasoning cannot happen unless students feel equipped to understand the concepts behind the formulas and have had experiencing developing their own versions of these types of representations.

Although there is a clear advantage to haptic learning methods which tap into intuitive understanding of structural performance, learning structures by only using one’s body has very specific limitations—our bodies can only create a handful of loading arrangements, can only endure a limited amount of stress, and our body forms and gestures can only be

used to communicate a small range of structural behaviors. Therefore, as a follow-up to the lab, students were asked to “translate” their personal experiences of structural behavior into representations that employed the more conventional means of representing structural behavior (to the extent that they understood it) in a lab report.

Lab reports are required to address the key learning objectives and questions put forth in the handout, and nearly always include: descriptions and representations of the group’s hypothesis (including early sketches), testing process (including weights and measures as needed), test results (mode of failure), a comparative analysis of results, and a conclusion of what was learned. These early lab reports are relatively open-ended in terms of the type of representations that are required. This flexibility gives students the leeway to experiment with different ways of best representing what they learned. Allowing students to craft a means of representation in support of an argument or as a demonstration of conceptual understanding is important as it gives the students opportunities to diversify their range of learning methodologies. Certain students focus on deductive analysis of particular components while others might use the same exercise but represent what they have learned with a more global learning perspective (e.g., showing how their tower structure was like the Eiffel Tower).

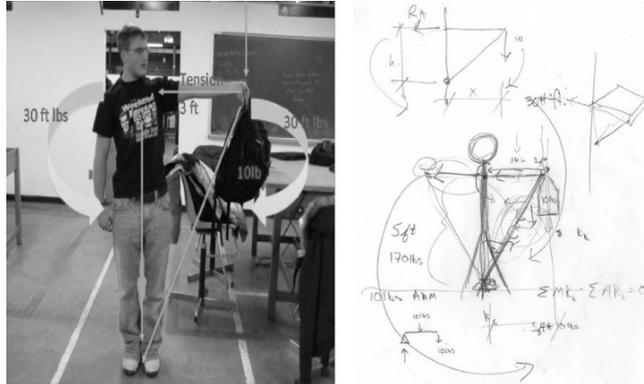


Figure 8: Sample from a student lab report using calculated force vectors to demonstrate states of equilibrium.

Students know at the beginning of the lab that they will need to represent the forces they felt—this requirement is included as a way of helping them better visualize the range of experiences they felt. While staging the scenarios, students make notes about the types of forces their bodies feel subjected to and where these stresses were felt. The lab reports are required to include diagrams of force vectors that indicate the type of stresses involved, diagrams of how equilibrium was maintained, and basic calculations of certain components in the system. Their lab write-up must incorporate proper use of structure terminology (loads, forces, stresses, stability, stiffness, strength, etc.) alongside these representations.

RESULTS & ASSESSMENTS:

Because only one class of students has completed all five courses of the new sequence and because so many factors have been reconfigured from the previous structures courses (different classroom setting / format, different teacher, new learning methods and resources, new tests/assignments and means of assessment, etc.) it’s difficult to accurately assess the learning results in terms of “before and after” efficacy. However, there is evidence that this first lab was influential not only in establishing a positive

learning environment, but that it contributed to a long-term strategy for helping students understand more complex structural behaviors.

Student evaluations for the new sequence been consistently higher than those for the previous courses, including markedly higher scores for questions asking students to assess how much they felt they learned, whether or not they felt the course was important to their education, and an overall assessment of the course's quality. Motivation also seems to have been improved. In the comments portion of the evaluation for this particular module, students frequently praised the interactive nature of the classroom and oftentimes mention the first laboratory as a positive (and often "fun") first experience.

Labs completed in subsequent semesters of the structural sequence showed an advanced level of comprehension of basic structure concepts and behaviors, along with more advanced abilities to create multimodal representations of these behaviors, including models, images, sketches, and written descriptions of experienced physical phenomena—as a result, the comprehensive design studio now occurs in conjunction with the final course in the sequence (in the fall of their fourth year)—a full year earlier than before the sequence was initiated. Later coursework also showed the lasting influence of this first lab. In the final module, students were assigned a comprehensive case study that included models, drawings, and written descriptions. Several different teams made frequent references, both in their descriptions of behavior and modes of representations, to the "body structure" as a way of explaining their conclusions.

One of the fundamental goals of this first lab, and the new structural curriculum sequence, was to help students realize that structural design is an accessible, exciting, and important component in architectural design. These first lab exercises provided a cognitive grounding in basic structural behavior (transferring knowledge from the abstract into more tangible realm) and presented a methodology for self-taught examination, analysis, and representations of basic structural concepts. The results suggest that one of the ways of developing a better conceptual understanding of basic structural behavior is to emphasize the importance of embodied cognition in interactive classroom environments. While it is not a direct reflection of improved student learning effectiveness, the course received a 2013 ACSA Creative Achievement Award.

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